Radiation Engineering for Designers

Jonathan A. Pellish

NASA Goddard Space Flight Center
Greenbelt, MD USA

September 2015

This work was sponsored in part by the NASA Electronic Parts and Packaging (NEPP) program and the NASA Engineering & Safety Center (NESC).

www.nasa.gov

To be published on nepp.nasa.gov originally published on https://nen.nasa.gov/.

Acronyms

Abbreviation	Deginition
AIEE	American Institute of Electrical Engineers
AO	Atomic Oxygen
ASIC	Application-Specific Integrated Circuit
CME	Coronal Mass Ejection
COTS	Commercial Off The Shelf
DDD	Displacement Damage Dose
DDR	Double Data Rate
DLA	Defense Logistics Agency
DRAM	Dynamic Random Access Memory
EEE	electrical, electronic, and electromechanical
ELDRS	Enhanced Low Dose Rate Sensitivity
EMI	Electromagnetic Interference
ESD	Electrostatic Discharge
ESP	Emission of Solar Protons
FPGA	Field Programmable Gate Array
GCR	Galactic Cosmic Ray
GEO	Geostationary Orbit
HEO	Highly Elliptical Orbit
IC	Integrated Circuit
IEEE	Institute of Electrical and Electronics Engineers
IRE	Institute of Radio Engineers
ISS	International Space Station
LDC	Lot Date Code
LED	Light Emitting Diode
LEO	Low Earth Orbit
LET	Linear Energy Transfer
MBU	Multiple Bit Upset
MCU	Multiple Cell Upset
MEO	Medium Earth Orbit
NEPP	NASA Electronic Parts and Packaging program
NESC	NASA Engineering & Safety Center
NIEL	Non-Ionizing Energy Loss
NPSS	Nuclear and Plasma Sciences Society
NSREC	Nuclear and Space Radiation Effects Conference

Abbreviation	Deginition
NWEs	Nuclear Weapons Effects
PCB	Printed Circuit Board
PKA	Primary Knock-On Atom
POC	Point of Contact
PSYCHIC	Prediction of Solar particle Yields for CHaracterizing Integrated Circuits
QML	Qualified Manufacturers List
QPL	Qualified Parts List
RDM	Radiation Design Margin
RH	Radiation Hardened
RHA	Radiation Hardness Assurance
RHBD	Radiation-Hardened By Design
RHBP	Radiation-Hardened By Process
RHBS	Radiation-Hardened By Serendipity
SAA	South Atlantic Anomaly
SAMPEX	Solar Anomalous Magnetospheric Explorer
SBU	Single Bit Upset
SDRAM	Synchronous Dynamic Random Access Memory
SEB	Single-Event Burnout
SEDR	Single-Event Dielectric Rupture
SEFI	Single-Event Functional Interrupt
SEGR	Single-Event Gate Rupture
SEL	Single-Event Latchup
SET	Single-Event Transient
SEU	Single-Event Upset
SiGe HBT	Silicon Germanium Heterojunction Bipolar Transistor
SMD	Standard Microcircuit Drawing
SOC	System-on-a-Chip
SOI	Silicon On Insulator
SOS	Silicon On Sapphire
SRAM	Static Random Access Memory
SSR	Solid State Recorder
TMR	Triple Modular Redundancy

Acknowledgements

- NASA Electronic Parts and Packaging (NEPP) program
- NASA Engineering & Safety Center (NESC)
- MSFC Electronic Design Branch
- MSFC Natural Environments Branch
- Many contributors across government and industry

What do you want to learn and gain from this tutorial?

A little history…

- Much of our community's history is captured in the evolution of the Nuclear and Space Radiation Effects Conference (NSREC), now an IEEE meeting run by the Nuclear and Plasma Sciences Society (NPSS).
  - First meetings were 1962/63, but still part of AIEE and IRE/AIEE. 1964 was first official IEEE NSREC.
  - In the beginning, lots of involvement from the nuclear weapons effects (NWE) community in addition to the civil and military space communities.
  - Just celebrated our 50th anniversary.

E. E. Conrad, "Reflections on 47+ Years of NSREC," presented at the IEEE Nuclear and Space Radiation Effects Conf., Denver, CO, Jul. 2010.

A little more history…

- Radiation community started during the Cold War
- Sputnik, 4 Oct 1957
- Van Allen Belts, Jan & Mar 1958 (Explorer I and III)
  - Army Ballistic Missile Agency in Huntsville, AL
- Space Race started; Space Act signed into law by President Eisenhower on 29 Jul 1958
- President Kennedy was in office
  - “Address at Rice University on the Nation's Space Effort” – “Going to the Moon Speech,” Sep 1961
- STARFISH PRIME, 9 Jul 1962
- Limited Test Ban Treaty, 5 Aug 1963

E. E. Conrad, "Reflections on 47+ Years of NSREC," presented at the IEEE Nuclear and Space Radiation Effects Conf., Denver, CO, Jul. 2010.

Course objectives

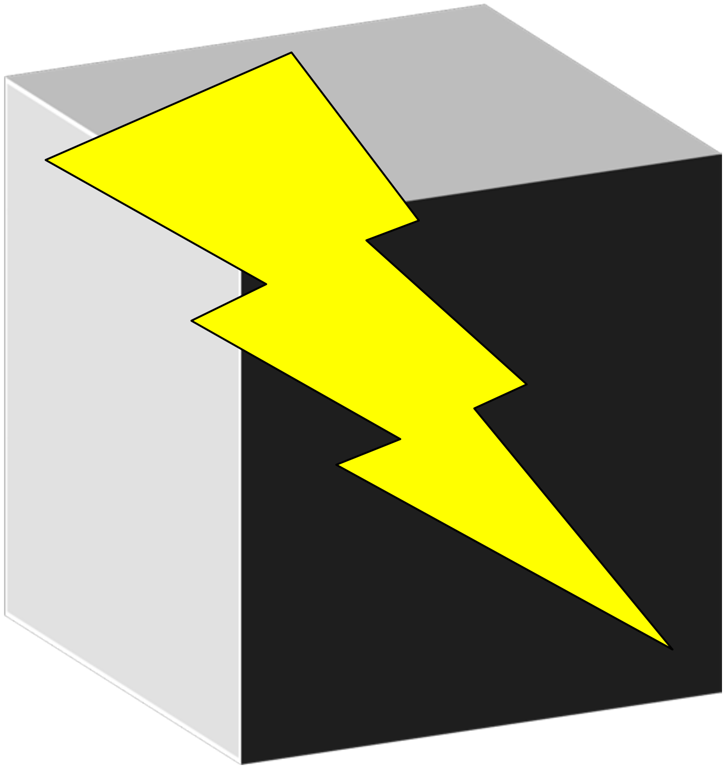
- After this tutorial, you will have:
  - An overview of the natural space radiation environment,
  - An introduction to radiation effect types,
  - An overview of EEE parts selection, scrubbing, and radiation mitigation, and
  - An introduction to radiation testing.
- After this tutorial, you will not:
  - Know everything about radiation effects, or
  - Glow in the dark.

My goals

- Increase knowledge of radiation effects amongst electrical designers and systems engineers.
- Urge electrical designers, system engineers, and management (line and project) to reach out for radiation effects expertise early in the development cycle.
- Encourage engineers and management to ask questions. We are here to learn.

Stop me any time to ask questions

What are radiation effects?



- Energy deposition rate in a “box”
- Source of energy and how it’s absorbed control the observed effects

What makes radiation effects so challenging?

- Field is still evolving as are the technologies we want to use
- A problem of dynamic range
  - Length: 10^{16} m → 10^{-15} m (1 light year, 1 fm)
    - » 10^{31}
  - Energy: 10^{19} eV → 1 eV (extreme energy cosmic ray, silicon band gap)
    - » 10^{19}
  - Those are just two dimensions; there are many others.
    - » Radiation sources, electronic technologies, etc.
- Variability and knowledge of the environment

To be published on nepp.nasa.gov originally published on https://nen.nasa.gov/.

Course sections

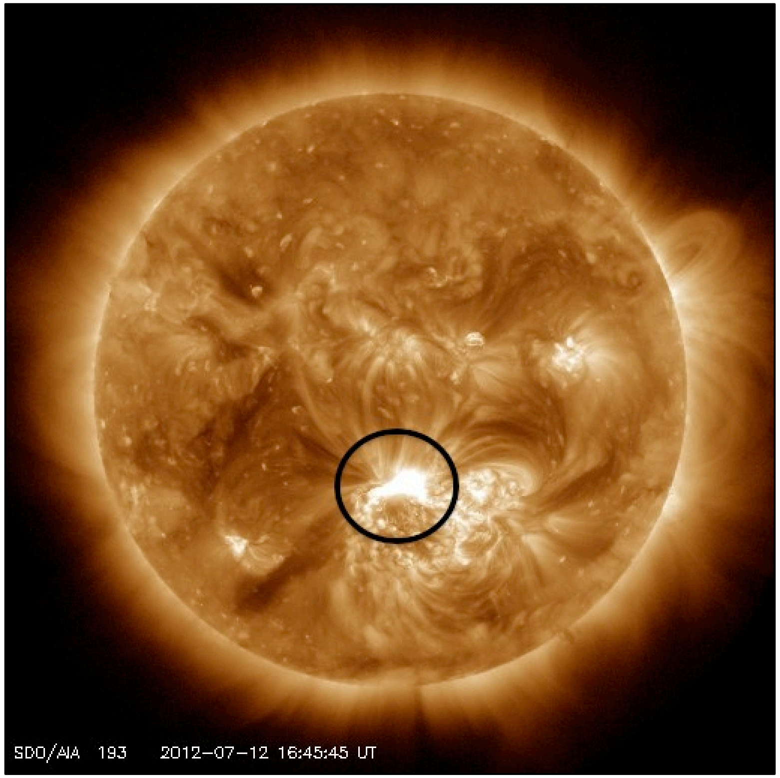
1. Introduction
2. **Natural space radiation environment**
3. Space environment impacts
4. Component selection and radiation effects mitigation
5. Radiation testing
6. Conclusion

NATURAL SPACE RADIATION ENVIRONMENT –

Particle Sources and Abundance

AR 1520 X1.4 flare and CME

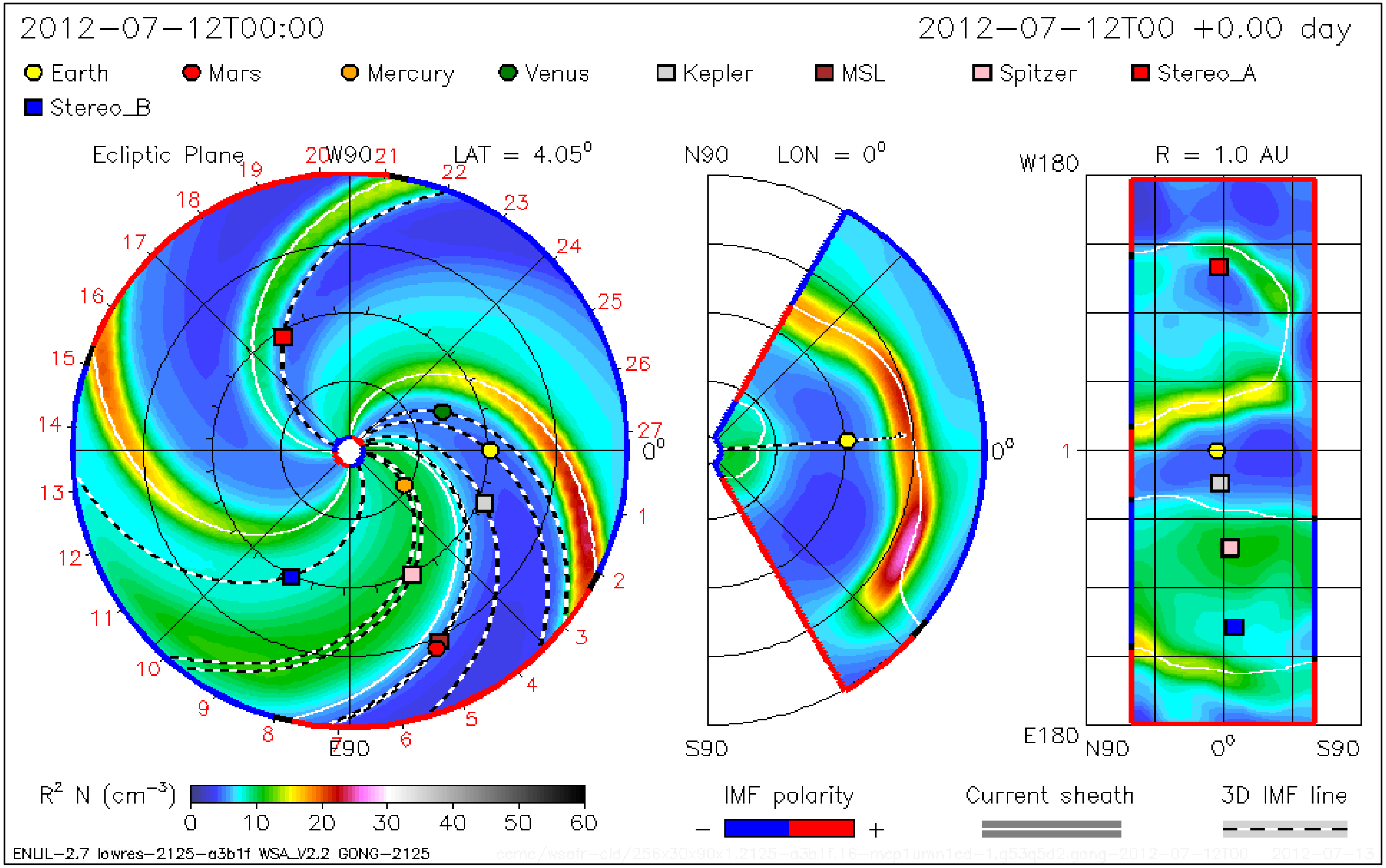
07/15/2012: a *K*p = 6 Geomagnetic Storm



Active Region 1520 circled

Left image captured with the NASA Solar Dynamics Observatory's Atmospheric Imaging Assembly
http://aia.lmsal.com/

CME's impact to Earth



Solar wind simulations from NASA/GSFC Integrated Space Weather Analysis System
http://iswa.ccmc.gsfc.nasa.gov/iswa/iSWA.html

Space environments

- Particle radiation – High-energy electrons, protons & heavy ions
  - Solar
  - Galactic cosmic rays (GCR)
  - Trapped in magnetospheres
- Plasma
  - Ionosphere
  - Plasmasphere – Magnetosphere
  - Solar wind
- Neutral gas particles
  - Lower – atomic oxygen (AO)
  - Higher – hydrogen & helium
- Ultraviolet and X-ray
- Micrometeoroids & orbital debris

Space radiation environment

- Space Weather
  - *“conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health”*

  [US National Space Weather Program]

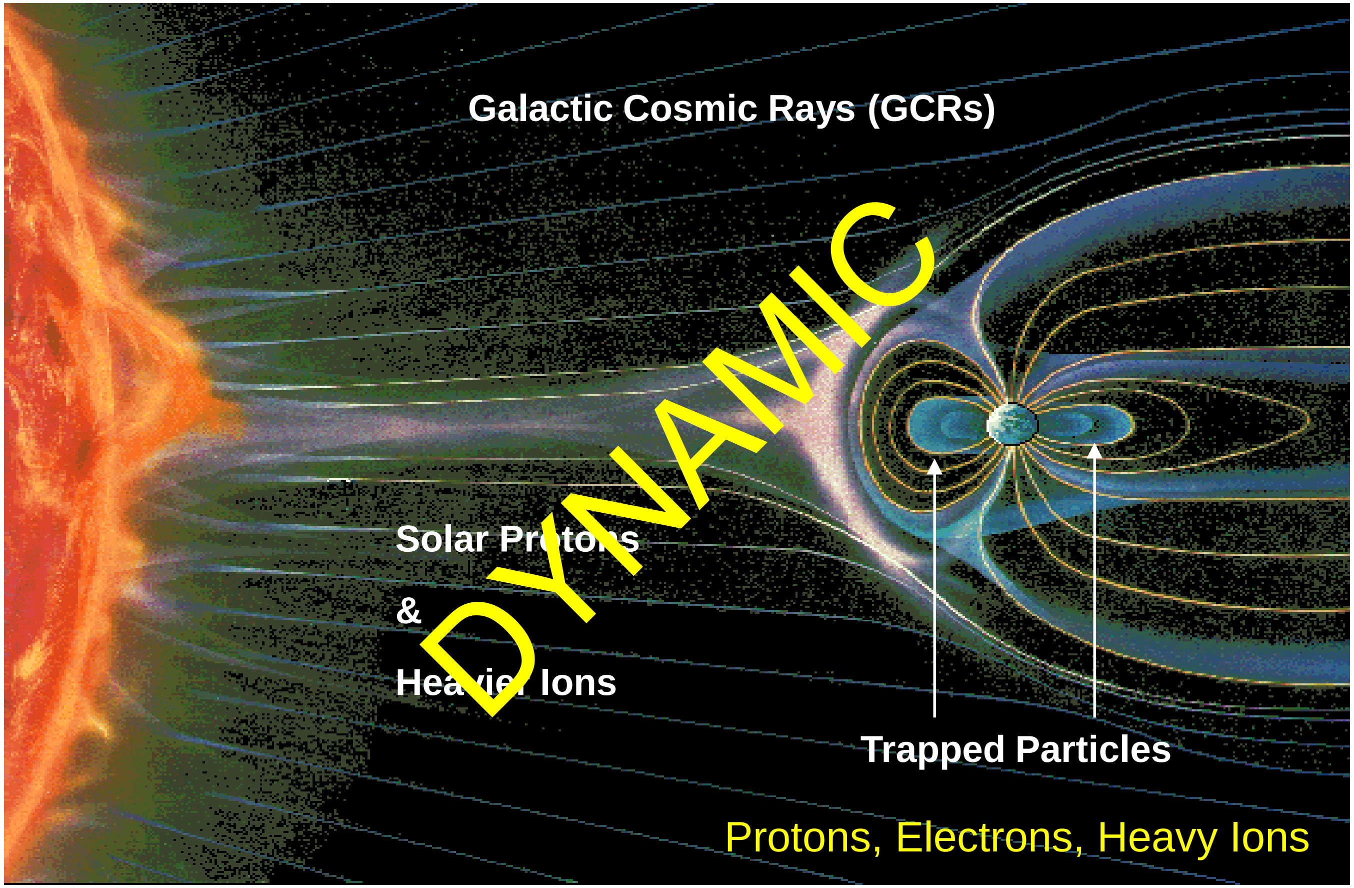
- <Space> Climate
  - “*The historical record and description of average daily and seasonal <space> weather events that help describe a region. Statistics are usually drawn over several decades*.”

  [Dave Schwartz the Weatherman – Weather.com]

- Goal of Radiation Hardness Assurance (RHA)
  - Design systems tolerant to the radiation environment within the level of risk acceptable for the mission.

M. A. Xapsos, et al., “Space Weather Effects on Spacecraft.” Spacecraft Anomalies and Failures Workshop, Chantilly, VA, 2013.

Natural Space Radiation Environment

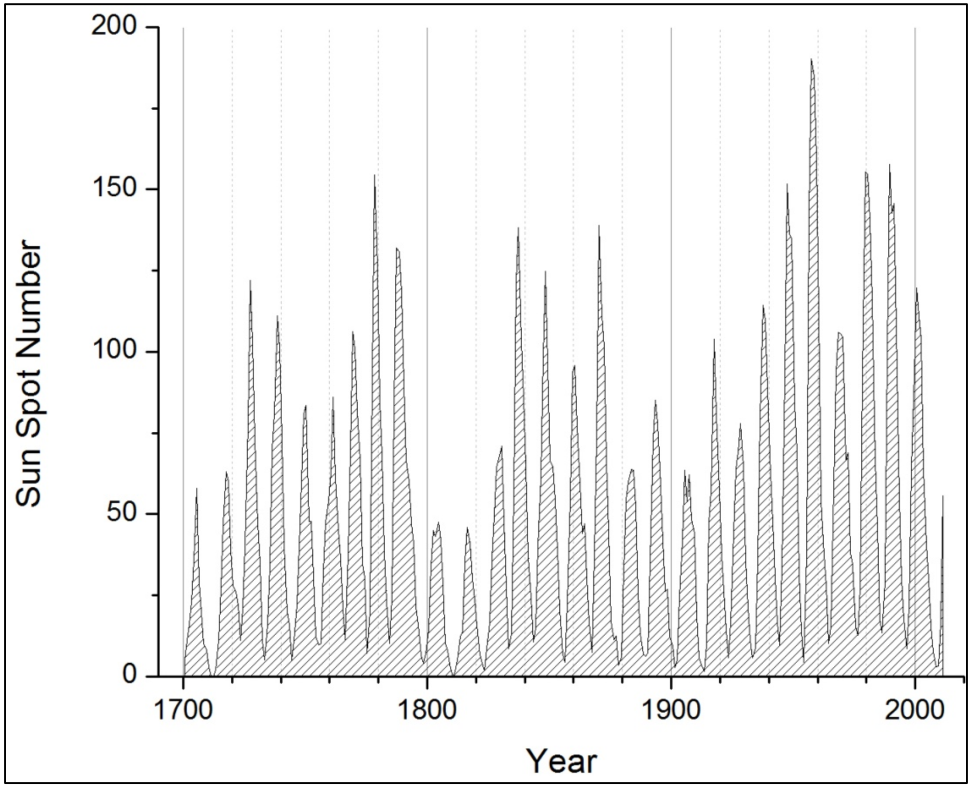


After J. Barth, 1997 IEEE NSREC Short Course; K. Endo, Nikkei Science Inc. of Japan; and K. LaBel private communication.

- Deep-space missions may also see neutrons and gamma rays from background or radioisotope sources

Solar Modulation

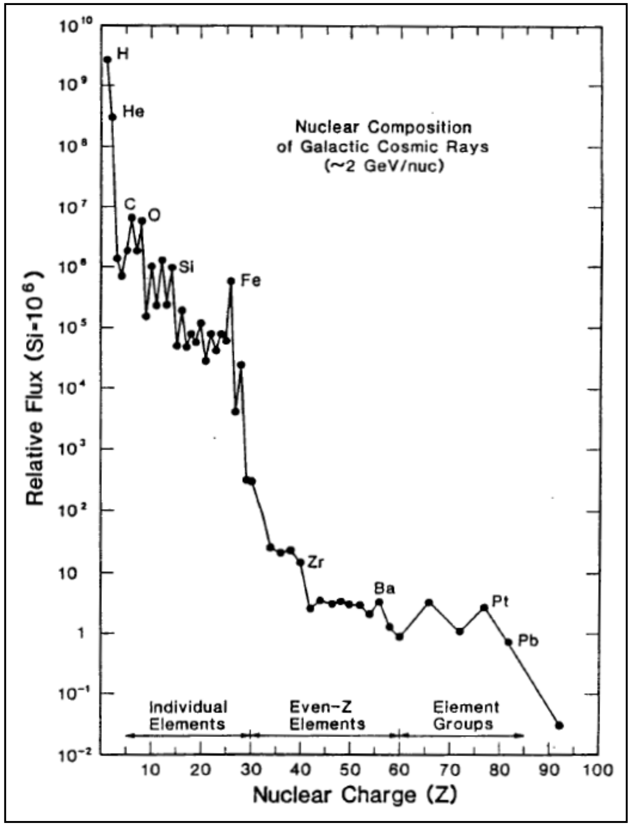
Yearly Sunspot Numbers



Data from the Solar Influences Data Analysis Center; http://sidc.oma.be/index.php

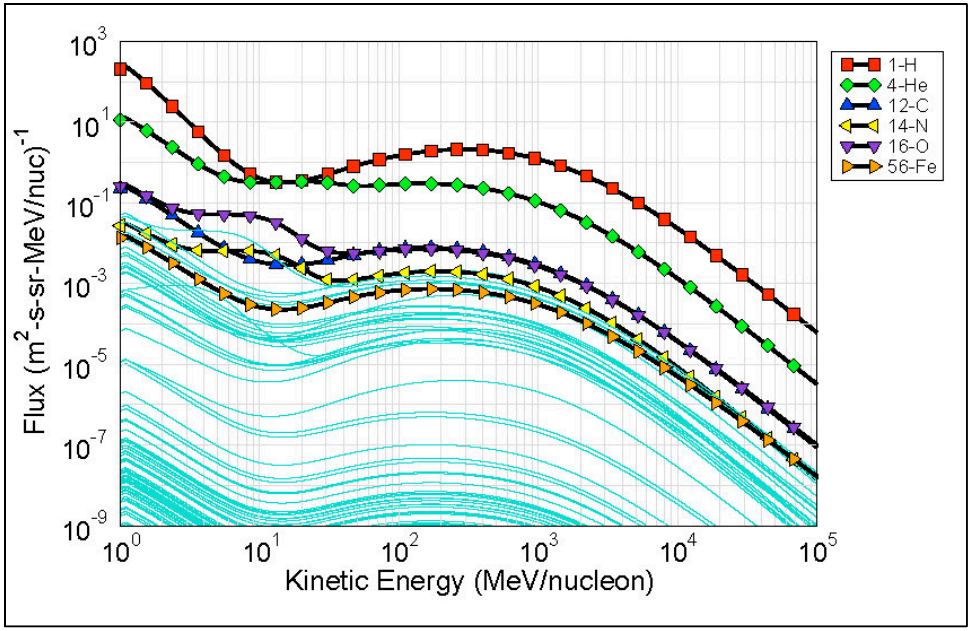
- 11- and 22-year solar activity cycles
    - 7 active years; 4 quiet years; polarity switch → 22-year cycle total
- Primarily affects cosmic rays and solar particles; not trapped particles

Galactic Cosmic Rays (GCRs)



R. A. Mewaldt, *Adv. in Space Res.*, 1994.

Nymmik 1992 Model, Geostationary Orbit

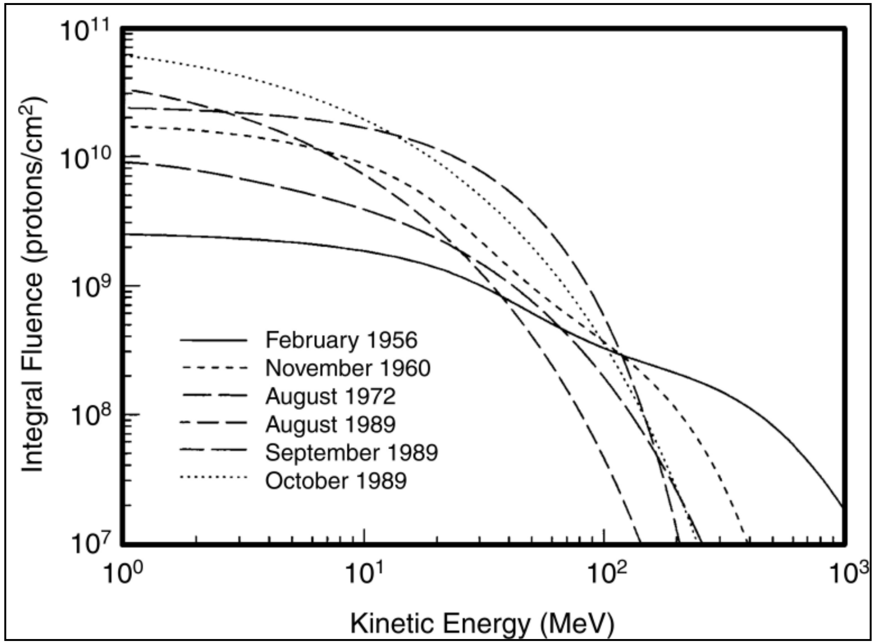


https://creme.isde.vanderbilt.edu/

- Originate outside the solar system (*e.g.*, supernovae)
- Include all naturally-occurring elements
  - Drops off rapidly for $Z > 26$ (iron)
- Most energetic of all space environment radiation

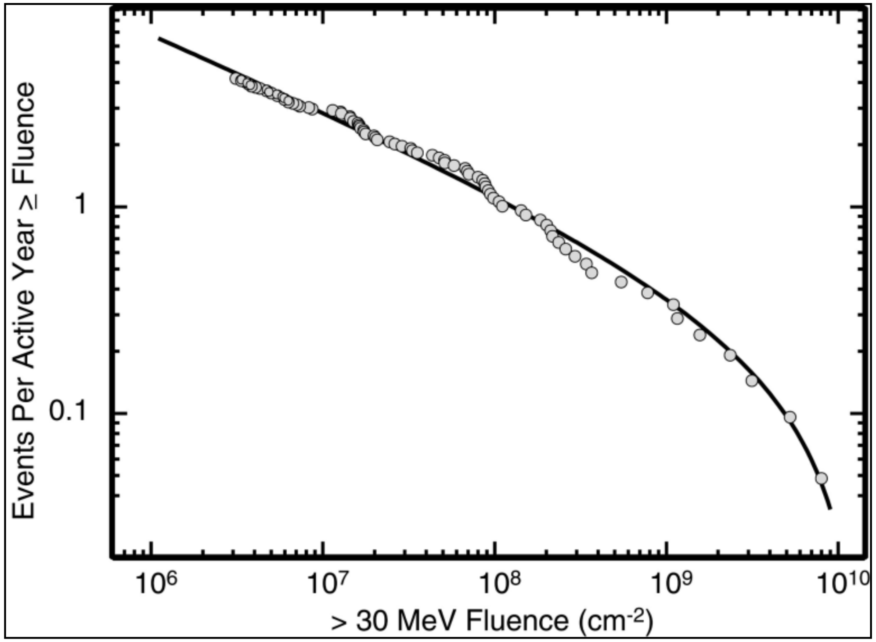
Solar Particle Events

Severe proton events from cycles 20-22



J. W. Wilson, *et al., Radiat. Meas.*, 1999.

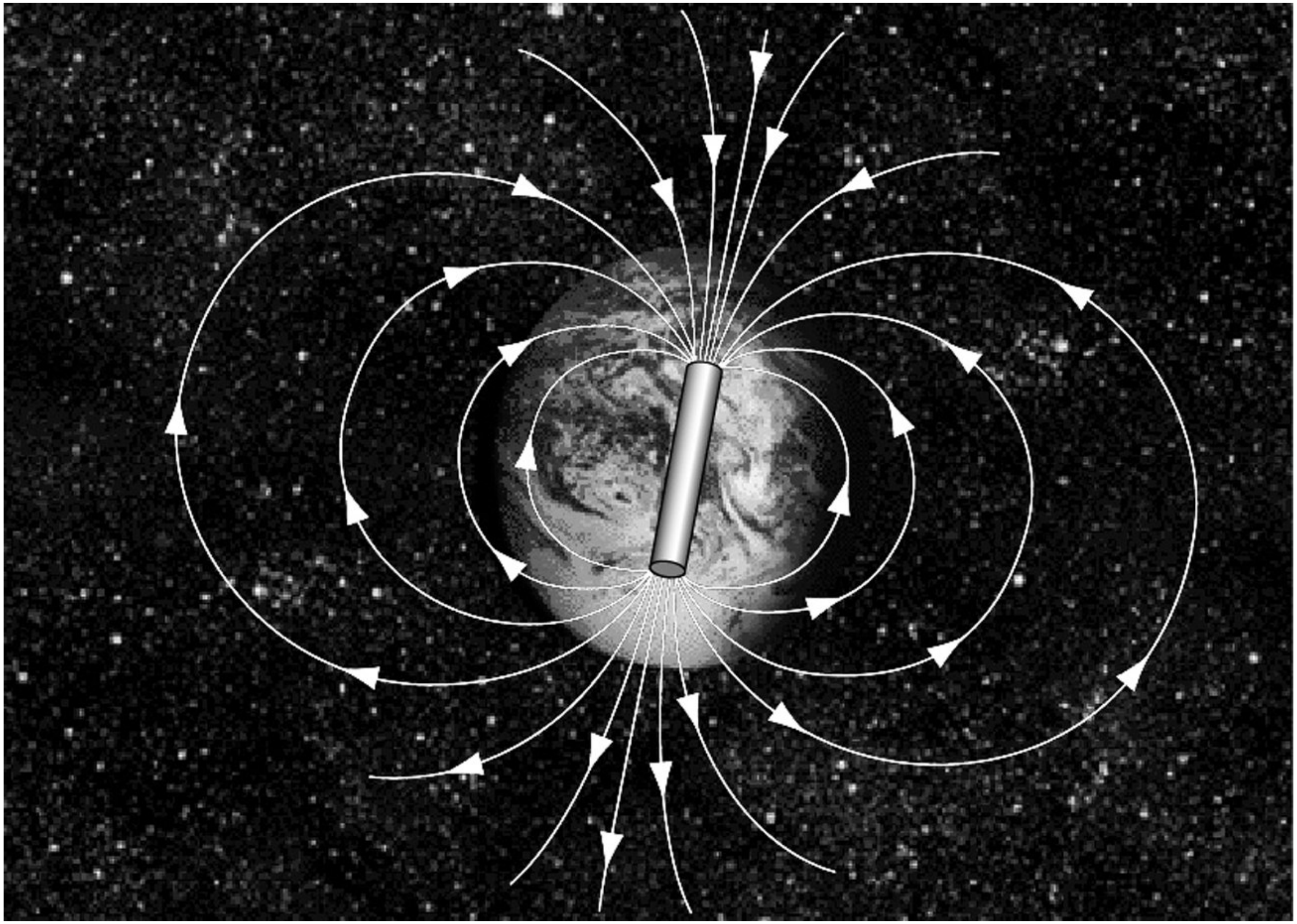
Maximum entropy model vs. data for cycles 20-22



M. A. Xapsos, *et al., IEEE TNS*, 1999.

- Solar flares & coronal mass ejections (CMEs)
  - Impulsive vs. gradual; magnetic field vs. plasma eruption
- CMEs primarily responsible for major interplanetary disturbances
- Energies are lower than galactic cosmic rays (GCR)

Trapped Particles

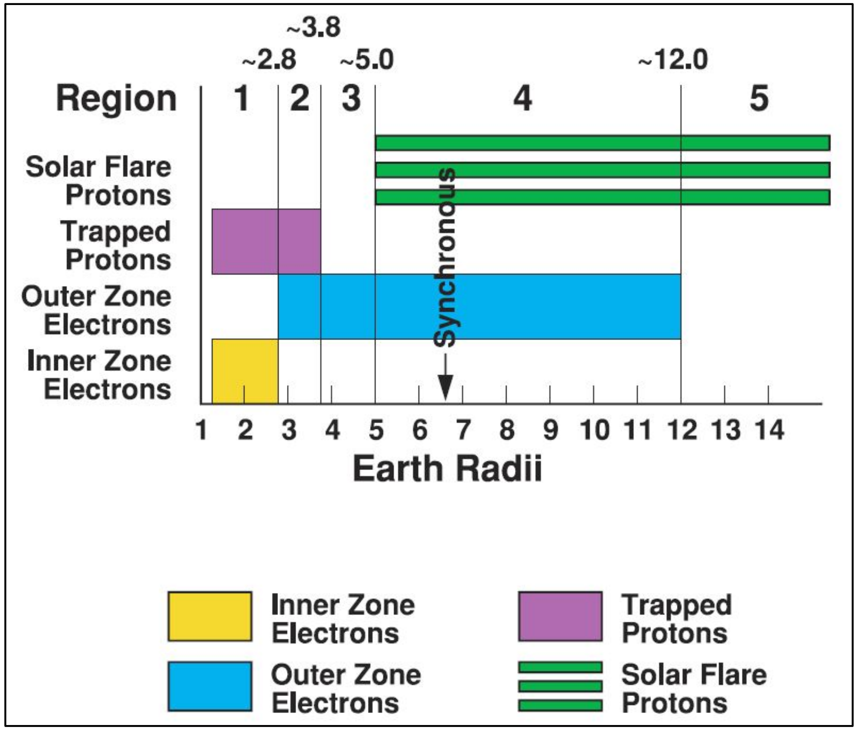


M. A. Xapsos, *IEEE NSREC Short Course*, 2006.

Trapped Particles

Note that extent of trapped protons only includes practical energies for electronic device radiation effects purposes.

The proton and electron populations are equal in order to achieve charge neutrality. The difference is based on kinetic energy within the population.

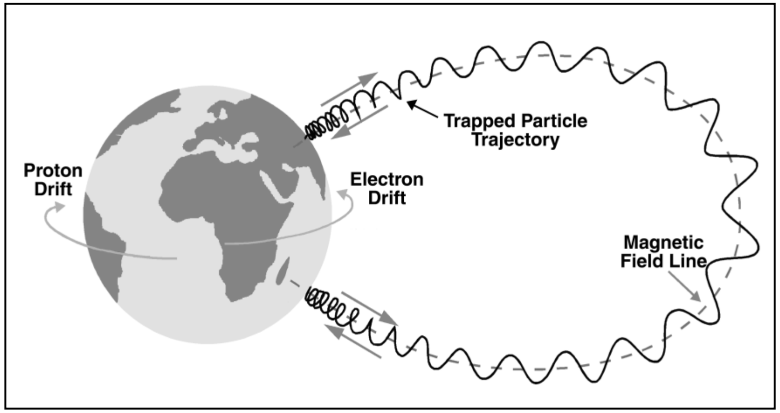


Courtesy of J. R. Schwank, *et al.*, after E. G. Stassinopoulos & J. P. Raymond, *Proc. IEEE,* Nov. 1988.

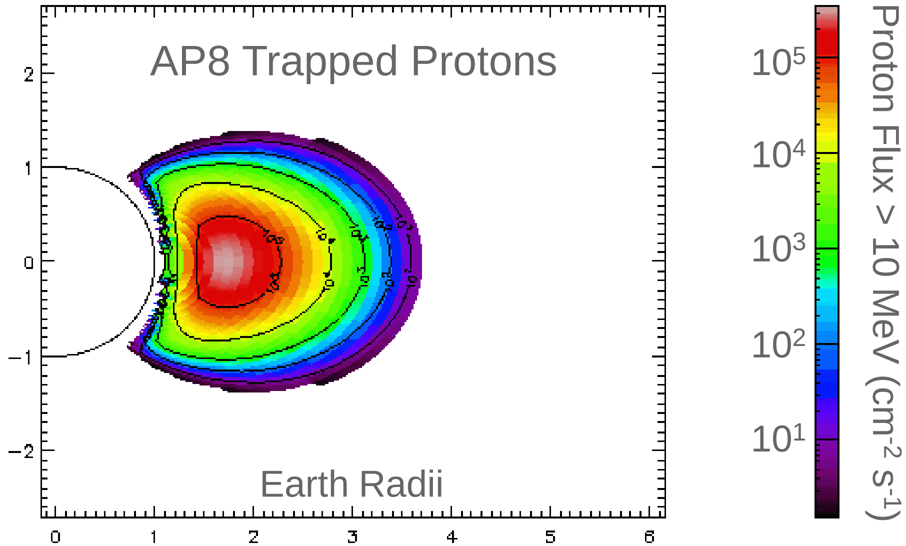
- Note the extent of the trapped protons and outer zone electrons, as well as the penetration range of solar flare protons.
- L-value often describes the set of magnetic field lines which cross the Earth's magnetic equator at a number of Earth-radii equal to the L-value.

Trapped Particles – Protons

- Localized to Earth's geomagnetic field
- Energies up to 100s of MeV
- > 10 MeV fluxes ~10^5 cm^{-2} s^{-1}
- *L*-shell 1.15 – 10
    - o Higher energy protons < 20,000 km
- ***Dipole offset***

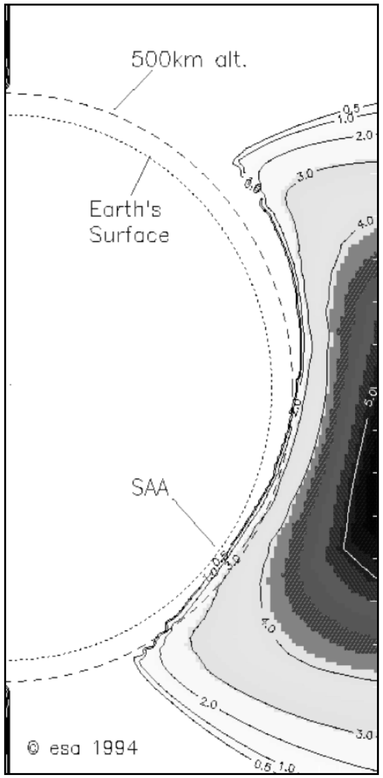


After E. G. Stassinopoulos & J. P. Raymond, *Proc. IEEE,* Nov. 1988 and W. N. Spjeldvik, *et al.*, Rep. AFGL-TR-83-0240, Hanscom AFB, MA, 1983.

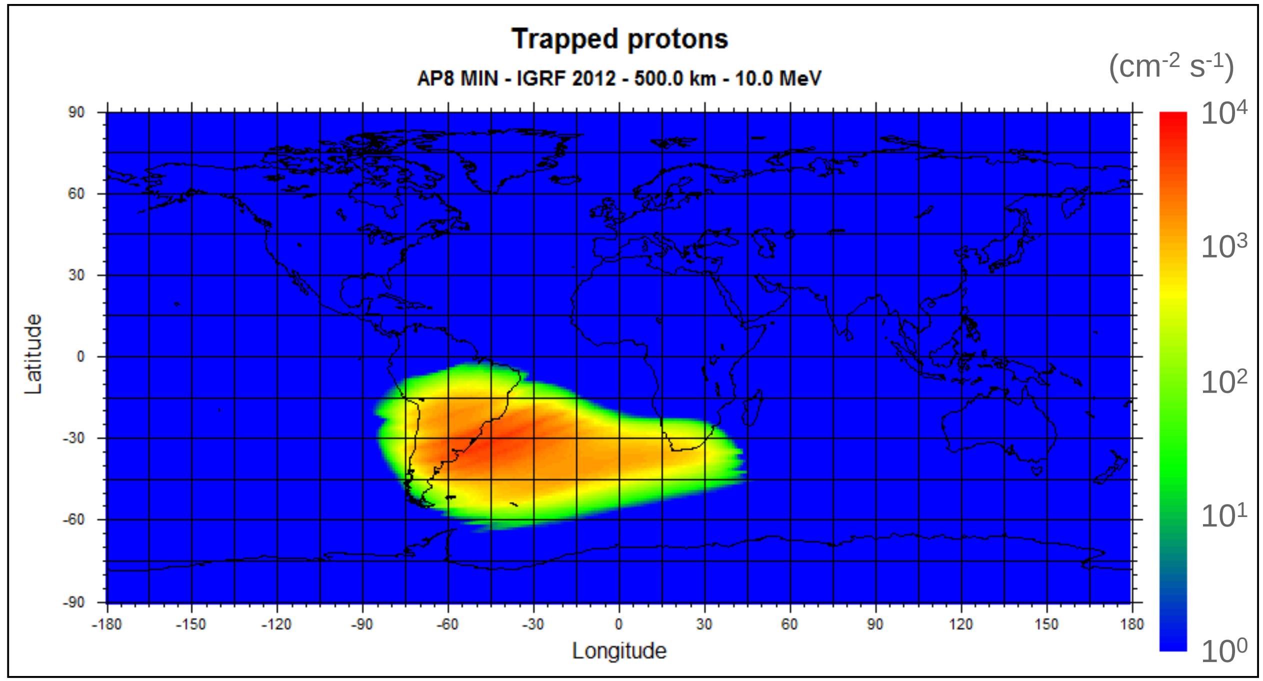


SPENVIS, http://www.spenvis.oma.be/, v4.6.5

Trapped Particles – Protons



E.J. Daly, *et al., IEEE TNS*, April 1996.

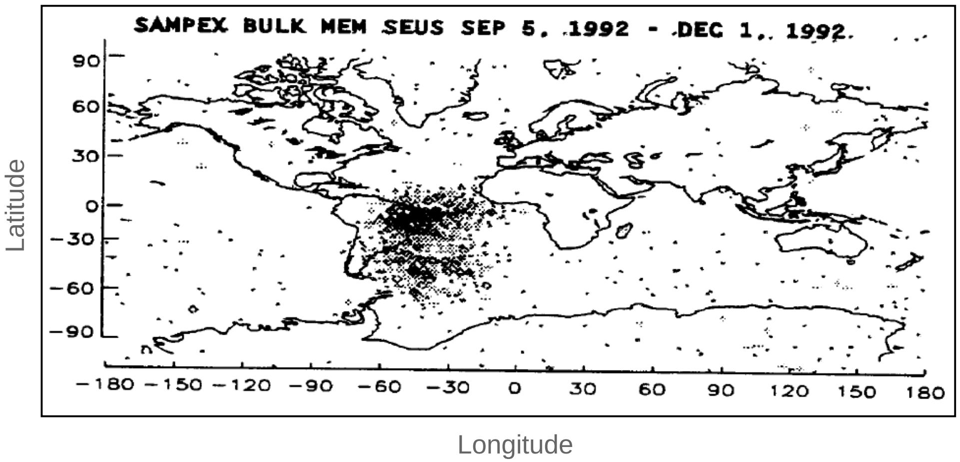


OMERE v3.4

- South Atlantic Anomaly (SAA) – dominates Earth's space environment below about 1000 km
- Due to tilt ***and*** displacement between rotational and geomagnetic axes

Effects of Trapped Protons

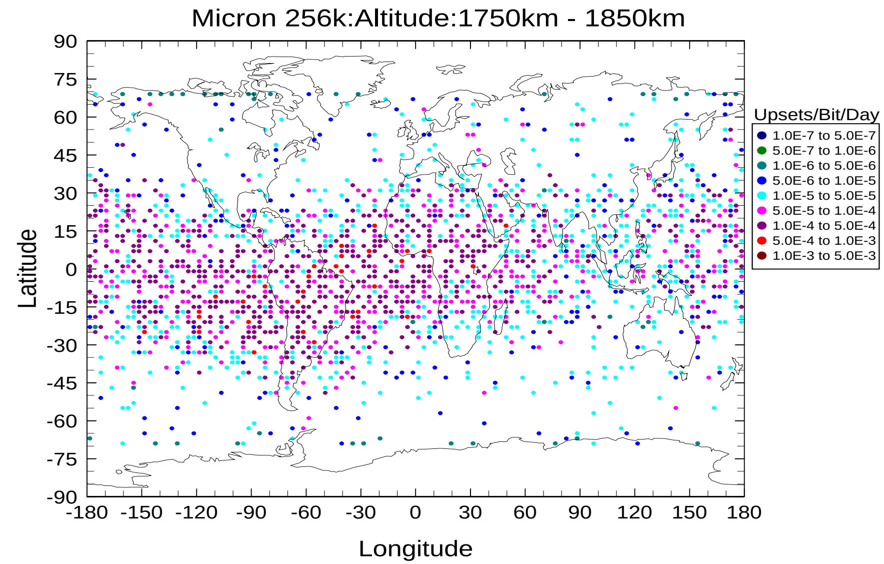
Solar Anomalous Magnetospheric Explorer (SAMPEX)
Solid State Recorder



K. A. LaBel, *et al.*, *IEEE REDW*, 1993.

SAMPEX was NASA's first Small Explorers mission

Cosmic Ray Upset Experiment (CRUX)
Advanced Photovoltaic and
Electronics Experiment (APEX)

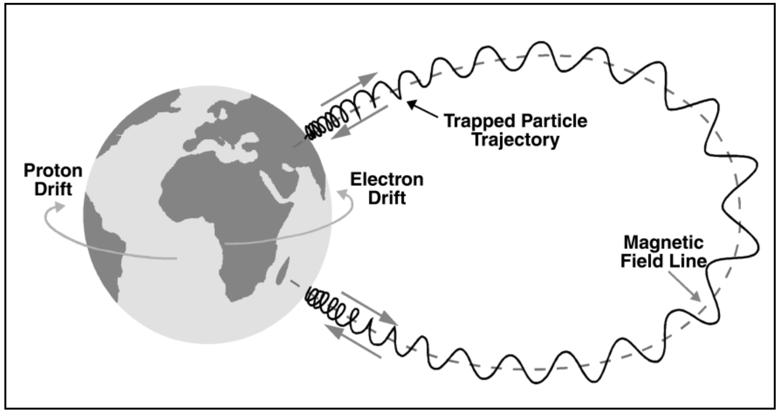


J. L. Barth, *et al.*, *IEEE TNS*, 1998.

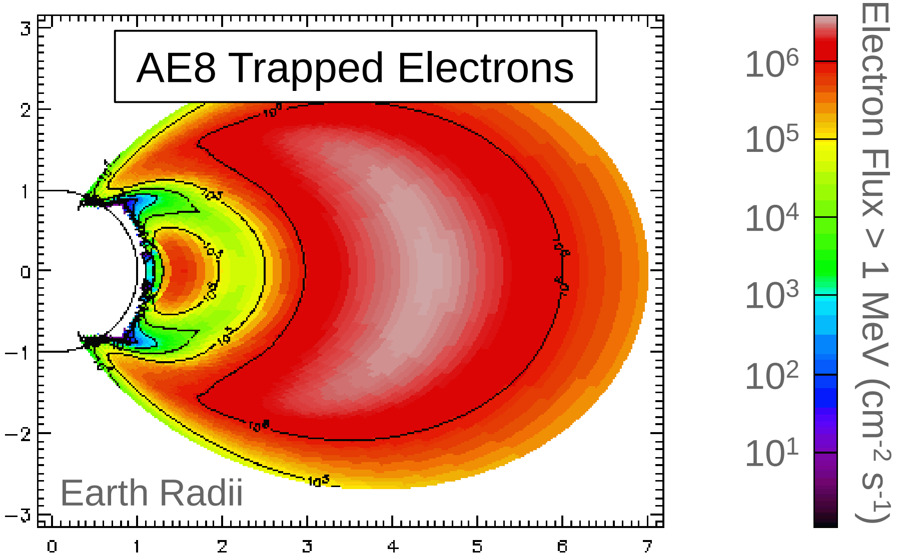
- Both the South Atlantic Anomaly and proton belts are visible in these on-orbit upset data

Trapped Particles – Electrons

- Localized to Earth's geomagnetic field
- Energies up to 10 MeV
- > 1 MeV fluxes up to ~10^6 cm^{-2} s^{-1}
- Two shells – inner and outer
  - o Inner: L-shell 1 – 2.8
  - o Outer: L-shell 2.8 – ~10
- Dominant feature for medium Earth orbit and geostationary vehicles



After E. G. Stassinopoulos & J. P. Raymond, *Proc. IEEE,* Nov. 1988 and W. N. Spjeldvik, *et al.*, Rep. AFGL-TR-83-0240, Hanscom AFB, MA, 1983.



After SPENVIS website, http://www.spenvis.oma.be

Radiation environments for different trajectories

Table based on content developed by K. A. LaBel, NASA GSFC.

	Plasma (charging)	Trapped Protons	Trapped Electrons	Solar Particles	Cosmic Rays	Nuclear Exposure
GEO	Yes	No	Yes	Yes	Yes	No
LEO (low-incl)	No	Yes	Moderate	No	No	No
LEO Polar	No	Yes	Moderate	Yes	Yes	No
ISS	No	Yes	Moderate	Yes - partial	Minimal	No
Interplanetary	Phasing orbits; possible other planet	Phasing orbits; possible other planet	Phasing orbits; possible other planet	Yes	Yes	Maybe
Exploration - MPCV	Phasing orbits	Phasing orbits	Phasing orbits	Yes	Yes	No
Exploration – Lunar, Mars	Phasing orbits	Phasing orbits	Phasing orbits	Yes	Yes	Maybe

General comments – not necessarily true in all cases. Yellow indicates hazard.

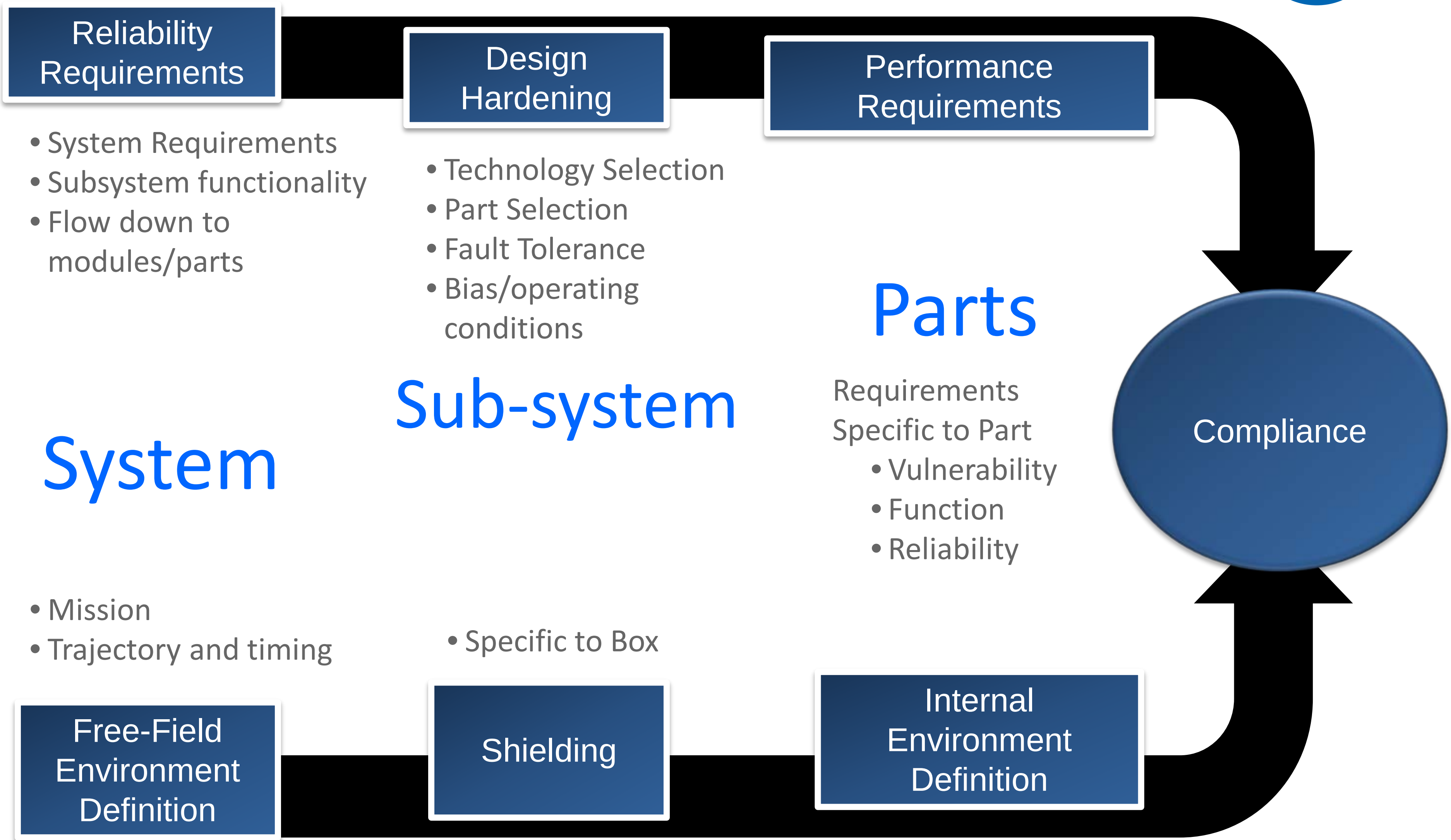
Relevant tools for simulation / prediction

- Trapped environments
  - SPENVIS (AP-8/AE-8, AP-9/AE-9, etc.)
  - CRÈME-MC (limited functionality)
  - Other packages
- Solar particle events (flares & CMEs)
  - SPENVIS (ESP, PSYCHIC, JPL-91, etc.)
  - Other packages
- Galactic Cosmic Rays
  - SPENVIS
  - CRÈME-MC
  - Other packages

Defining environment requirements

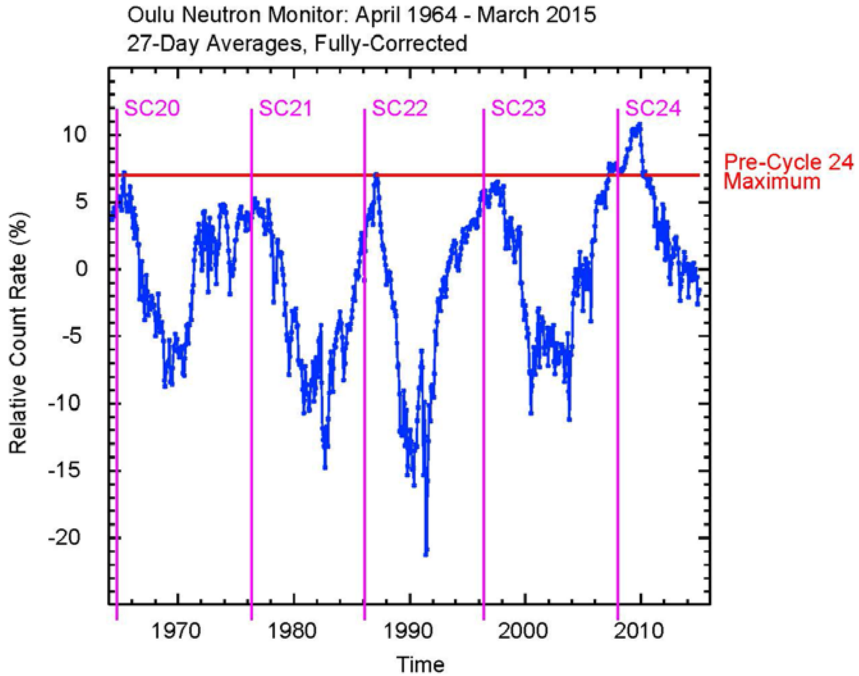
- Drives cost, schedule, and technical margin
- Must be comprehensive
- Complete <u>early</u> in the design cycle

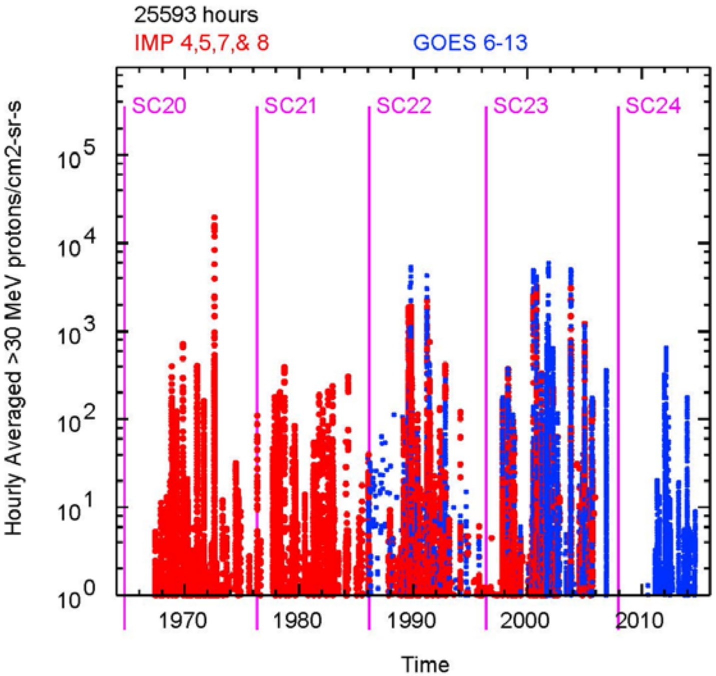
Requirements process



Adapted from R. Gigliuto, ASRC Space and Defense, “System-level Effects and Radiation Testing,” Nov 2008.

Space environment challenges





A. J. Tylka, “The Solar Energetic Particle (SEP) Radiation Hazard,” NAC Subcommittee Briefing, Apr 2015.

- In the 2008-2010 minimum of solar activity, we saw a higher flux of Galactic Cosmic Rays (GCRs) at Earth than ever seen before in the Space Age.
- Does this difference have implications for future missions, manned and/or robotic?

Top space environment challenges

- Loss of communications with STEREO-B spacecraft on 1 Oct 2014
  - Impacts space weather prediction capabilities
- Space climate vs. space weather
  - Designing mission requirements with a static environment – reality is quite dynamic

Environment topics not covered…

- Surface and deep dielectric charging
  - Including plasma effects (EMI, ESD, etc.)
- Atomic oxygen
- Micrometeoroids
- Orbital debris

Course sections

1. Introduction
2. Natural space radiation environment
3. **Space environment impacts**
4. Component selection and radiation effects mitigation
5. Radiation testing
6. Conclusion

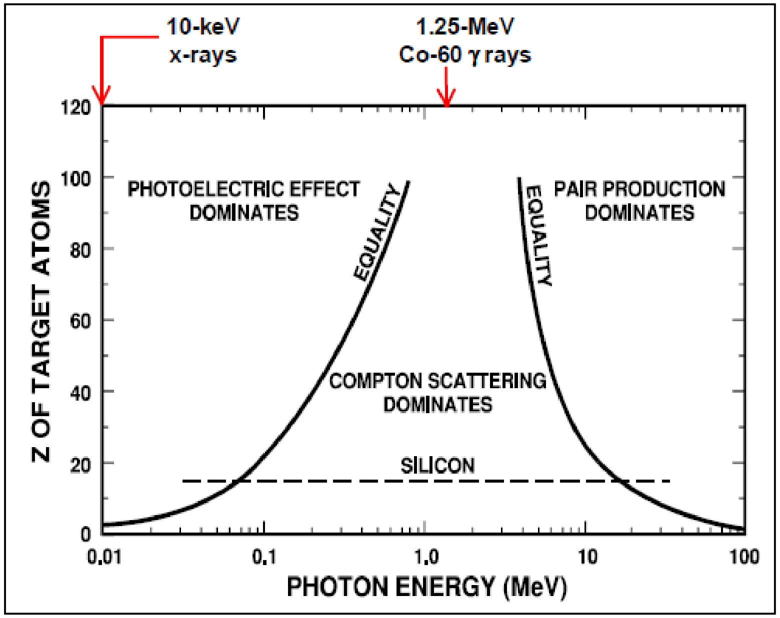
SPACE ENVIRONMENT IMPACTS –
Radiation effects are caused by the deposition of energy in materials

What is a rad?

- 1 rad = 100 erg/g = 0.01 J/kg; 100 rad = 1 Gy
  - Always specified for a particular material
  - 1 rad(SiO_2), 10 krad(Si), 100 Gy(H_2O)
- This is absorbed dose, not exposure (R), or dose equivalent (Sv)
- Missions have a wide range of absorbed dose requirements, driven in large part by persistent environment components
  - Trapped particles, solar protons, etc.

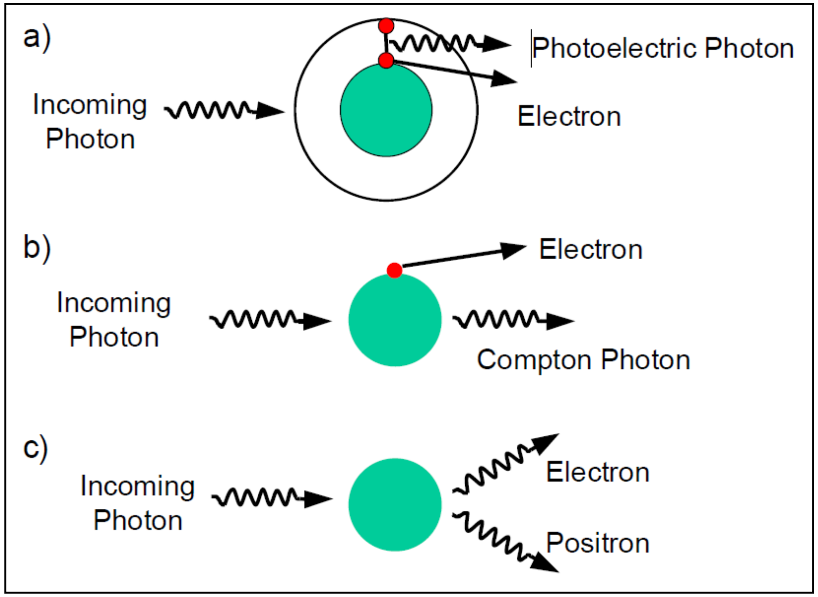
Photons deposit energy too

Photon Effects



J. R. Schwank, *IEEE NSREC Short Course*, 2002;
after R. D. Evans, *The Atomic Nucleus*, 1955.

Photon-Material Interactions



J. R. Schwank, *IEEE NSREC Short Course*, 2002; after
F. B. McLean and T. R. Oldham, Harry Diamond Laboratories Tech. Report, 1987.

- Incoming particles – electrons, protons, heavy ions, and photons – can deposit energy in semiconductor materials
- Energy becomes “hot” electron-hole pairs

What is total ionizing dose?

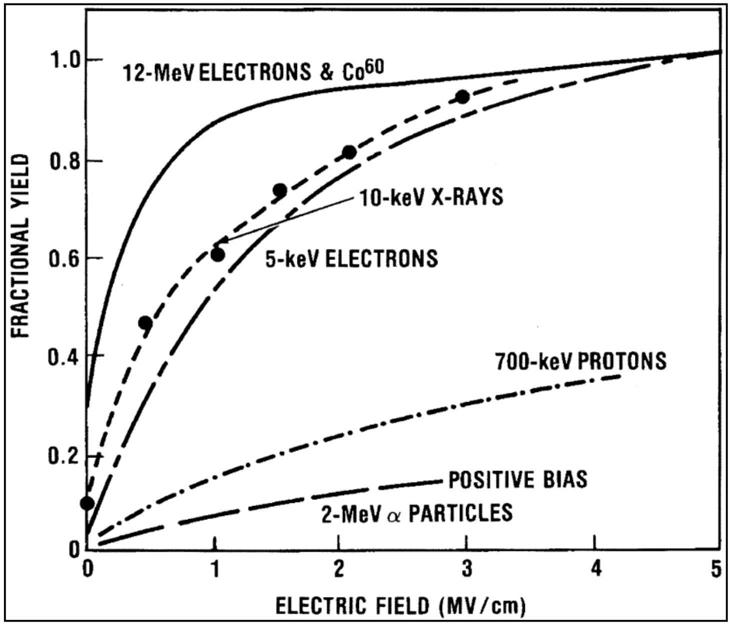
- Total ionizing dose (TID) is the absorbed dose in a given material resulting from the energy deposition of ionizing radiation.
- Total ionizing dose results in cumulative parametric degradation that can lead to functional failure.
- In space, caused mainly by protons and electrons.

Examples

Metal Oxide Semiconductors Devices	Bipolar Devices
Threshold voltage shifts	Excess base current
Increased off-state leakage	Changes to recombination behavior

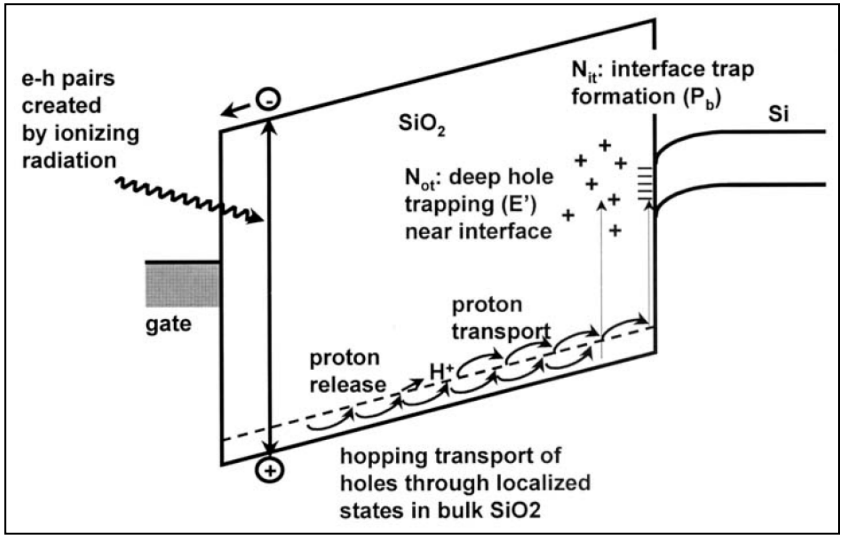
Total ionizing dose

Fractional Hole Yield by Particle Type



T. R. Oldham and J. M. McGarrity, *IEEE TNS*, 1983.
T. R. Oldham and F. B. McLean, *IEEE TNS*, 2003.

Processes Involved in TID Damage

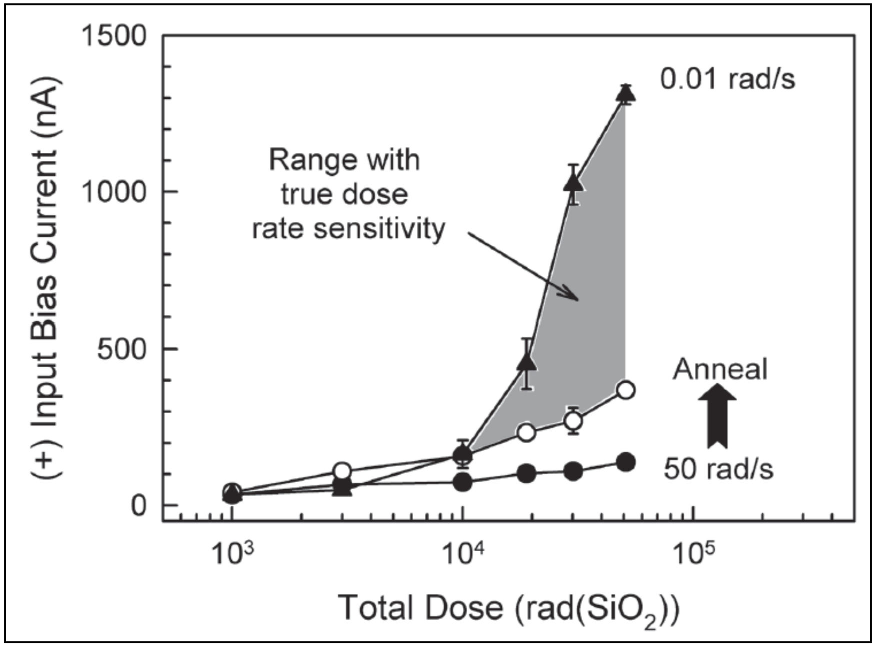


F. B. McLean and T. R. Oldham, Harry Diamond Laboratories Tech. Report, 1987.
T. R. Oldham and F. B. McLean, *IEEE TNS*, 2003.

- Caused by the energy deposition of protons, electrons, energetic heavy ions, and photon-material interactions – ***focused on insulators***
- Holes build up in deep traps and interface traps, which are manifest as electrical changes in device performance

ELDRS effects in bipolar devices

I_{B+} *vs.* Total Dose for LM111 Voltage Comparators

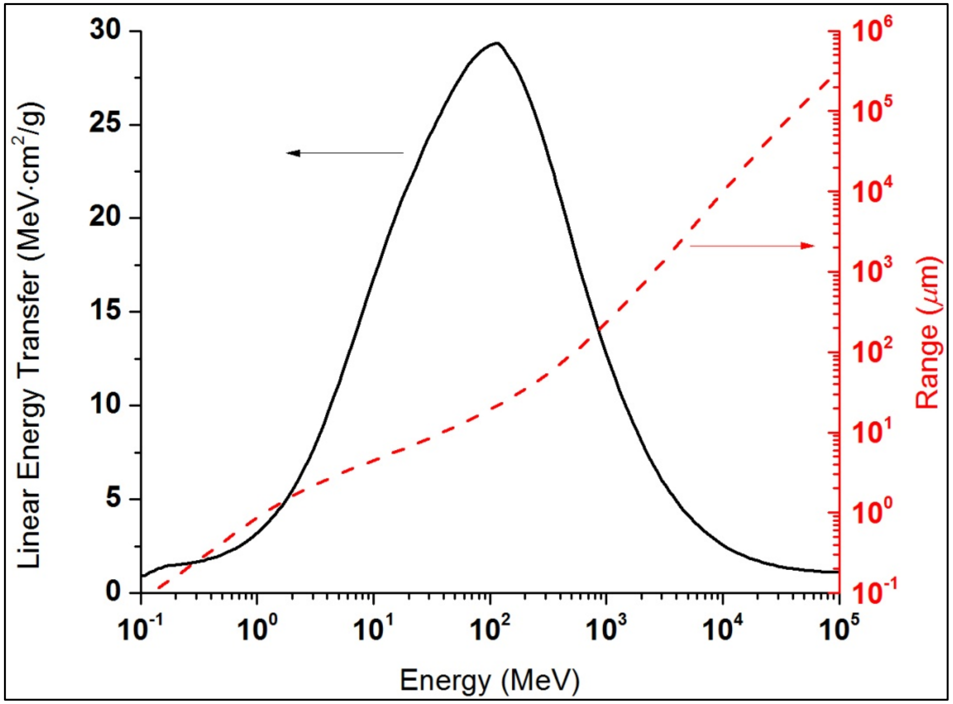


M. R. Shaneyfelt, et al., *IEEE TNS*, 2000.

- First observed in bipolar devices and circuits in the early 1990s
- Amount of total dose degradation at a given total dose is greater at low dose rates than at high dose rates
    - True dose-rate effect as opposed to a time-dependent effect

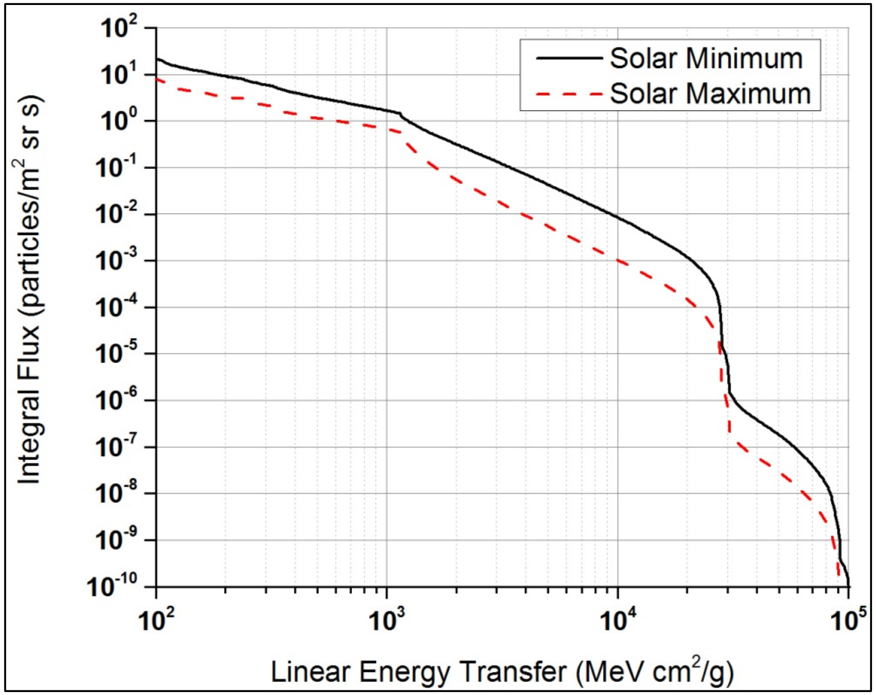
Ions & linear energy transfer (LET)

Iron in Silicon



Generated with SRIM-2008

LET Spectrum behind 2.5 mm of Aluminum



Generated with CREME96

$$S = -\frac{dE}{dx} \Rightarrow \mathrm{LET} = -\frac{1}{\rho}\frac{dE}{dx}$$

Stopping power (S), depends on target material; LET does not

What are single-event effects?

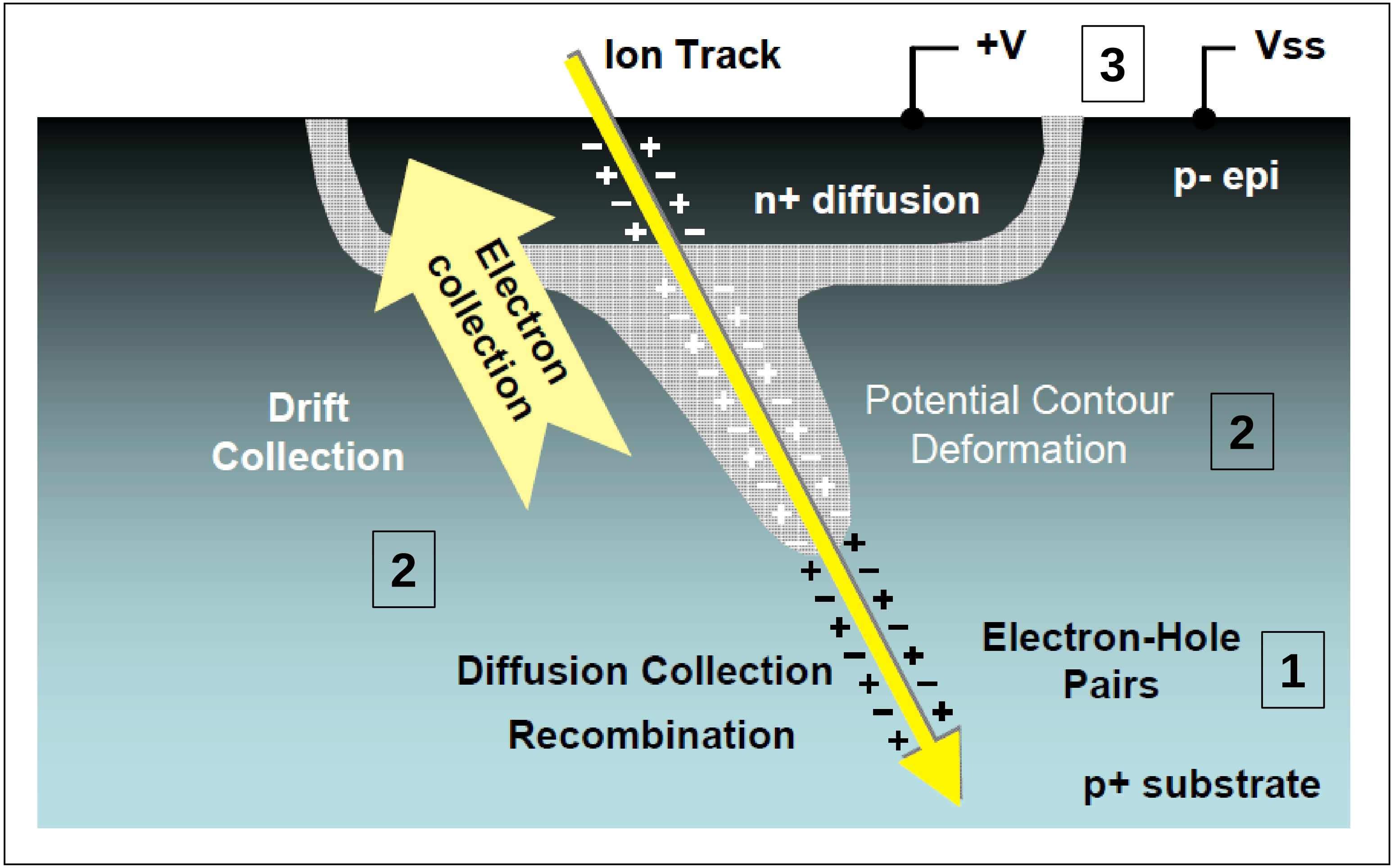
- A single-event effect (SEE) is a disturbance to the normal operation of a circuit caused by the passage of a single ion (proton or heavy ion) through or near a sensitive node in a circuit.
- SEEs can be either destructive or non-destructive.

Examples

<table>
<tr><th>Non-Destructive</th><th>Destructive</th></tr>
<tr><td>Single-Event Upset (SEU)</td><td>Single-Event Latchup (SEL)</td></tr>
<tr><td>Multiple-Bit Upset (MBU)</td><td>Single-Event Burnout (SEB)</td></tr>
<tr><td>Single-Event Transient (SET)</td><td rowspan="2">Single-Event Gate Rupture (SEGR)</td></tr>
<tr><td>Single-Event Functional Interrupt (SEFI)</td></tr>
</table>

After S. Buchner, *SERESSA 2011 Course*, Toulouse, France.

Single-event effects processes



R. Baumann, *IEEE NSREC Short Course*, Seattle, WA, 2005.

Short history of single-event effects

After S. Buchner, *SERESSA 2011 Course*, Toulouse, France.

- The possibility of single event upsets was first postulated in 1962 by Wallmark and Marcus. ***J.T. Wallmark**, S.M. Marcus, "Minimum size and maximum packaging density of non-redundant semiconductor devices," Proc. IRE, vol. 50, pp. 286-298, March 1962.*
- The first actual satellite anomalies were reported in 1975. SEUs in flip-flops. ***D. Binder**, E.C. Smith, A.B. Holman, "Satellite anomalies from galactic cosmic rays," IEEE Trans. on Nuclear Science, vol. 22, no. 6, pp. 2675-2680, Dec. 1975.*
- First observation of SEUs on earth was in 1978. Observed in RAM caused by the alpha particles released by U and Th contaminants within the chip packaging material and solder. Vendors took specific actions to reduce it. ***T. C. May and M. H. Woods**, "A New Physical Mechanism for Soft Errors in Dynamic Memories", Proceedings 16 Int'l Reliability Physics Symposium, p. 33, April, 1978.*
- First report of SEUs due to cosmic rays on earth in 1979. ***J. F. Ziegler** and W. A. Lanford, "Effect of Cosmic Rays on Computer Memories", Science, 206, 776 (1979).*
- First report of destructive SEE (proton induced latch-up) in a memory operating in space in 1992 **L. Adams** *et al.*, *"A Verified Proton Induced Latch-up in Space," IEEE TNS vol. 39, No. 6, pp. 1804 – 1808, Dec. 1992.*

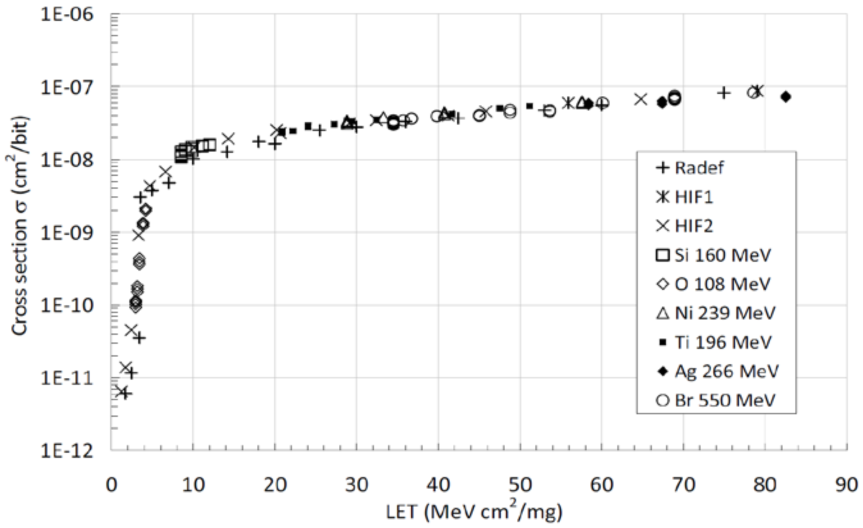
Proton SEE notes

- Proton LET is very low (<< 1 MeV-cm^2/mg)
    - Upsets are usually dominated by indirect ionization – nuclear reactions
    - Reaction products have appreciable LETs, usually less than 15 MeV-cm^2/mg, but short ranges compared to GCRs
- Importance of proton SEE
    - In proton-dominated environments, can be a large portion of the overall SEE rate – LEO, for instance

After S. Kayali, "Space Radiation Effects on Microelectronics," http://parts.jpl.nasa.gov/docs/Radcrs_Final.pdf.

Calculating SEE rates

- Measure cross section (σ) vs. LET
  - Testing done with particle accelerators (protons and heavy ions)
  - Cross section based on circuit response
- Determine sensitive volume
  - Need to make assumptions about device construction
  - Used to determine the effect of ions that strike the device at angle (it's an isotropic environment)



After D. Bisello, et al., "SEU cross section measurement of the ESA SEU monitor," *Laboratori Nazionali di Legnaro Annual Report, 2012.*

SEE rate calculation development

Milestone	Date	Authors
First reported SEU in space	1975	Binder, Smith and Holman
LET distribution concept is introduced	1977	Heinrich
First reported alpha particle upset in ground-based ICs	1979	May and Woods
Development of heavy ion SEU rate prediction model based on distributions of path length and LET	1978, 1980	Pickel and Blandford
First observations of proton-induced SEU	1979	Wyatt, McNulty, Toumbas, Rothwell and Filz Guenzer, Wolicki and Allas
Development of semi-empirical model for proton SEU rate	1983	Bendel and Petersen
CRÈME suite of codes combine environment and rate prediction tools in standardized package	1986	Adams
Development of Effective Flux approach for heavy ion SEU rate	1988	Binder

R. A. Reed, *et al., IEEE TNS*, 2003.

SEE rates – traditional *vs.* Monte Carlo

- Traditional rate calculation models and methods fall short in some cases – *work well in others*
  - Angular dependence & low-energy proton effects
  - Bipolar effects in SOI CMOS
  - Charge collection by diffusion
  - Heavy ion indirect ionization
  - Ion track structure effects
  - Thick sensitive volumes
- Solution requires representation of additional physics and an augmented description of the system under simulation

SEE rates – let's roll dice

- Monte Carlo simulation provides a path forward since an analytical solution is not required. It can invoke:
  - Quantitative description of the relevant radiation environment(s)
  - Transport of the incident radiation through any materials or structures that surround the sensitive circuitry
  - Energy deposition in the electronic materials by the impinging radiation
  - Conversion of energy into charge
  - Charge transport and recombination in the semiconductor and insulator regions
  - Transistor-level response, including effects of charge deposited by incident radiation
  - Circuit response, including radiation-induced transients

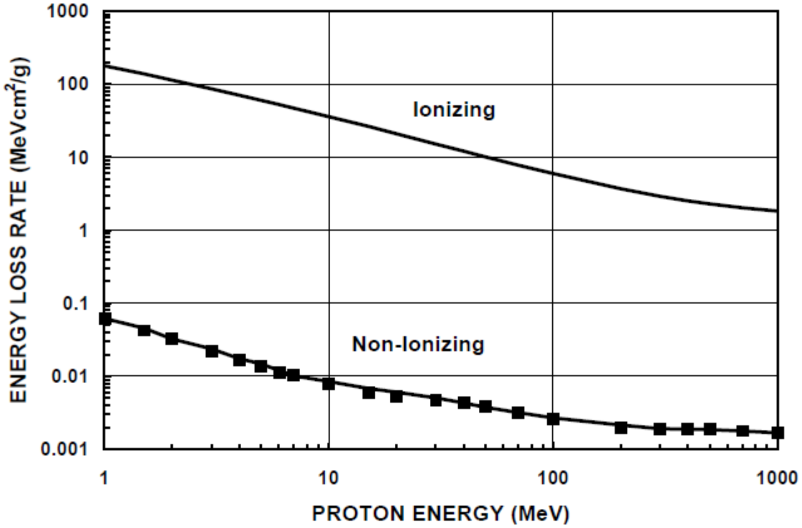
After R. A. Weller, *et al.*, *IEEE TNS*, 2010.

What is NIEL?

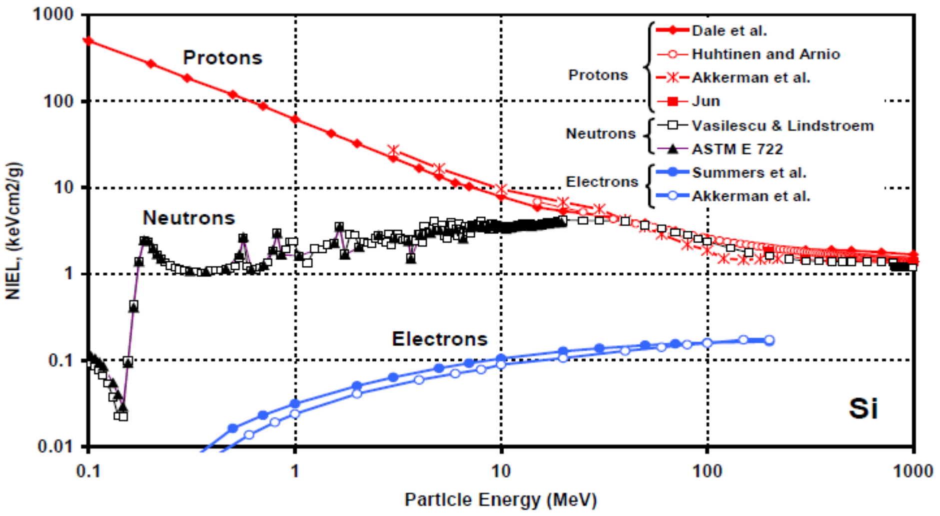
- Most always applies to protons and electrons.
- Vast majority of incident kinetic energy lost to ionization, creating TID and single-event effects.
- A small portion of energy lost in non-ionizing processes causes atoms to be removed from their lattice sites and form permanent electrically active defects (i.e., displacement damage) in semiconductor materials.
- NIEL (non-ionizing energy loss) is that part of the energy introduced via both Coulomb (elastic), nuclear elastic, and nuclear inelastic interactions, which produces the initial vacancy-interstitial pairs and phonons (e.g., vibrational energy).

What is NIEL?

Silicon Material System



After C. J. Marshall, 1999 IEEE NSREC Short Course.



After C. Poivey & G. Hopkinson, “Displacement Damage Mechanism and Effects,” Space Radiation and its Effect on EEE Components, EPFL Training Course, 2009.

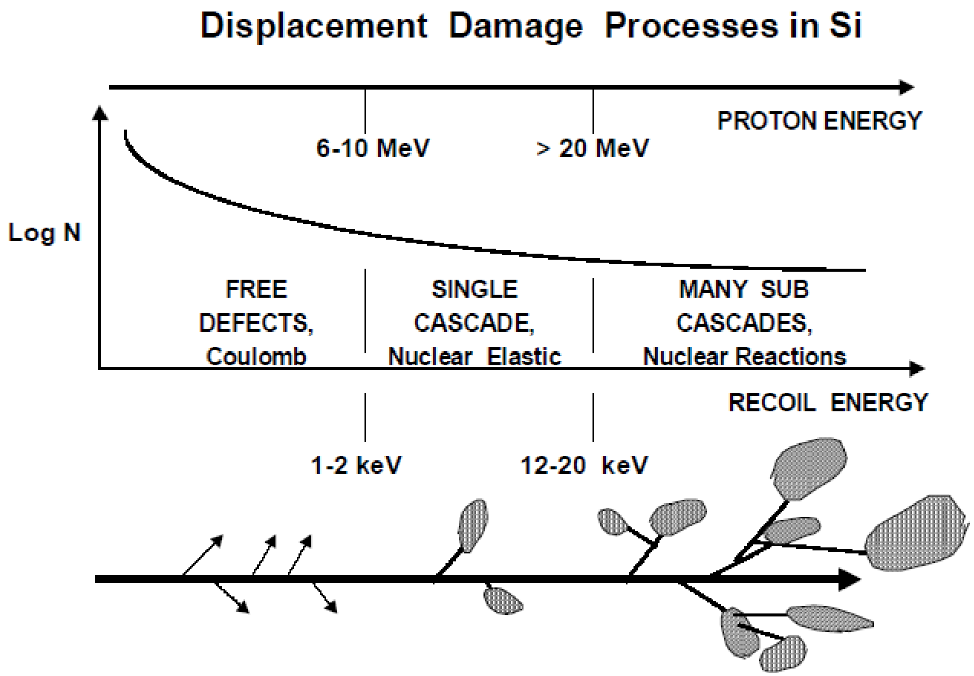
- Non-ionizing energy causes cumulative damage, much like TID

What is displacement damage?

- Displacement damage dose (DDD) is the non-ionizing energy loss (NIEL) in a given material resulting from a portion of energy deposition by impinging radiation.
- DDD is cumulative parametric degradation that can lead to functional failure.
- In space, caused mainly by protons and electrons.

DDD Effects
Degraded minority carrier lifetime (e.g., gain reductions, effects in LEDs and optical sensors, etc.)
Changes to mobility and carrier concentrations

NIEL, visually



After C. J. Marshall, 1999 IEEE NSREC Short Course.

- Pictorial relating the initial defect configuration to the primary knock-on atom (PKA) energy in Si material.
- For recoil energies above a couple of keV, the overall damage structure is relatively unchanged due to the formation of cascades and sub-cascades.

Course sections

1. Introduction
2. Natural space radiation environment
3. Space environment impacts
4. **Component selection and radiation effects mitigation**
5. Radiation testing
6. Conclusion

COMPONENT SELECTION AND RADIATION EFFECTS MITIGATION –

Protect this spacecraft

Before we get started…

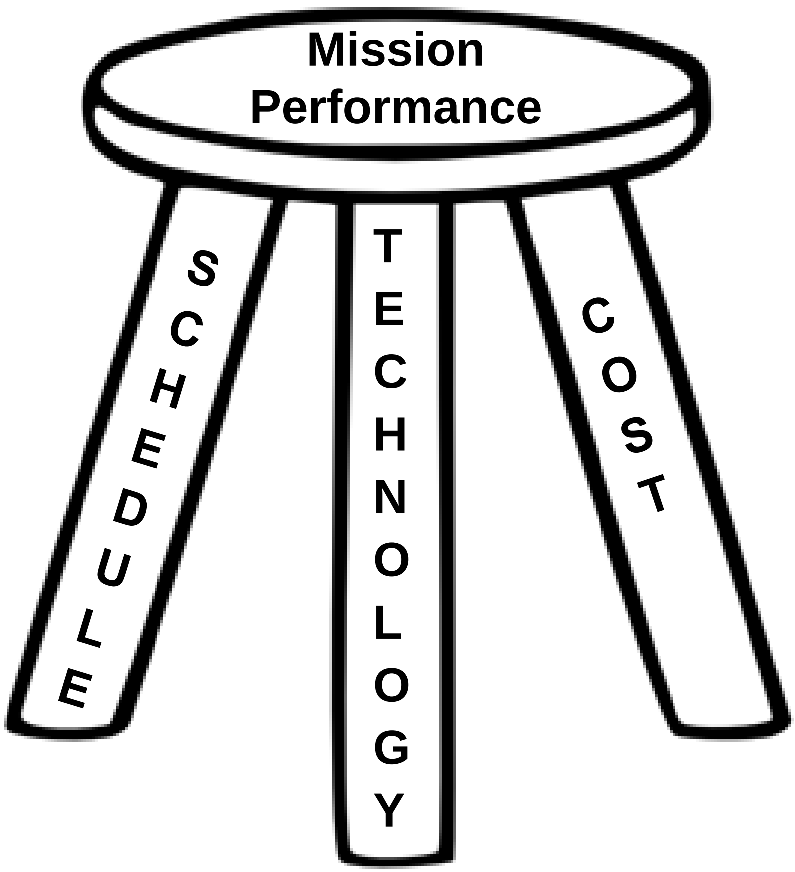
- A significant amount of material in this section was developed by Ken LaBel, Code 561, NASA/GSFC (thank you!)
  - Practices we have used for many years, which may or may not fit the character of your program
  - In general, they are relevant and applicable

Perspective is everything

- The Design Engineer has the specialist's viewpoint. Views the system from the inside.
  - Concerned with other system elements only as they affect their own design task; but not necessarily how theirs may affect others
- The Systems Engineer has the systems viewpoint. Views the system from the outside.
  - Concerned with the effect of all system elements as they affect overall system design / performance / cost / schedule
- The Radiation Effects Engineer has to have both a systems viewpoint and a specialist’s viewpoint

R. Gigliuto, ASRC Space and Defense, “System-level Effects and Radiation Testing,” Nov 2008.

Pieces of mission performance

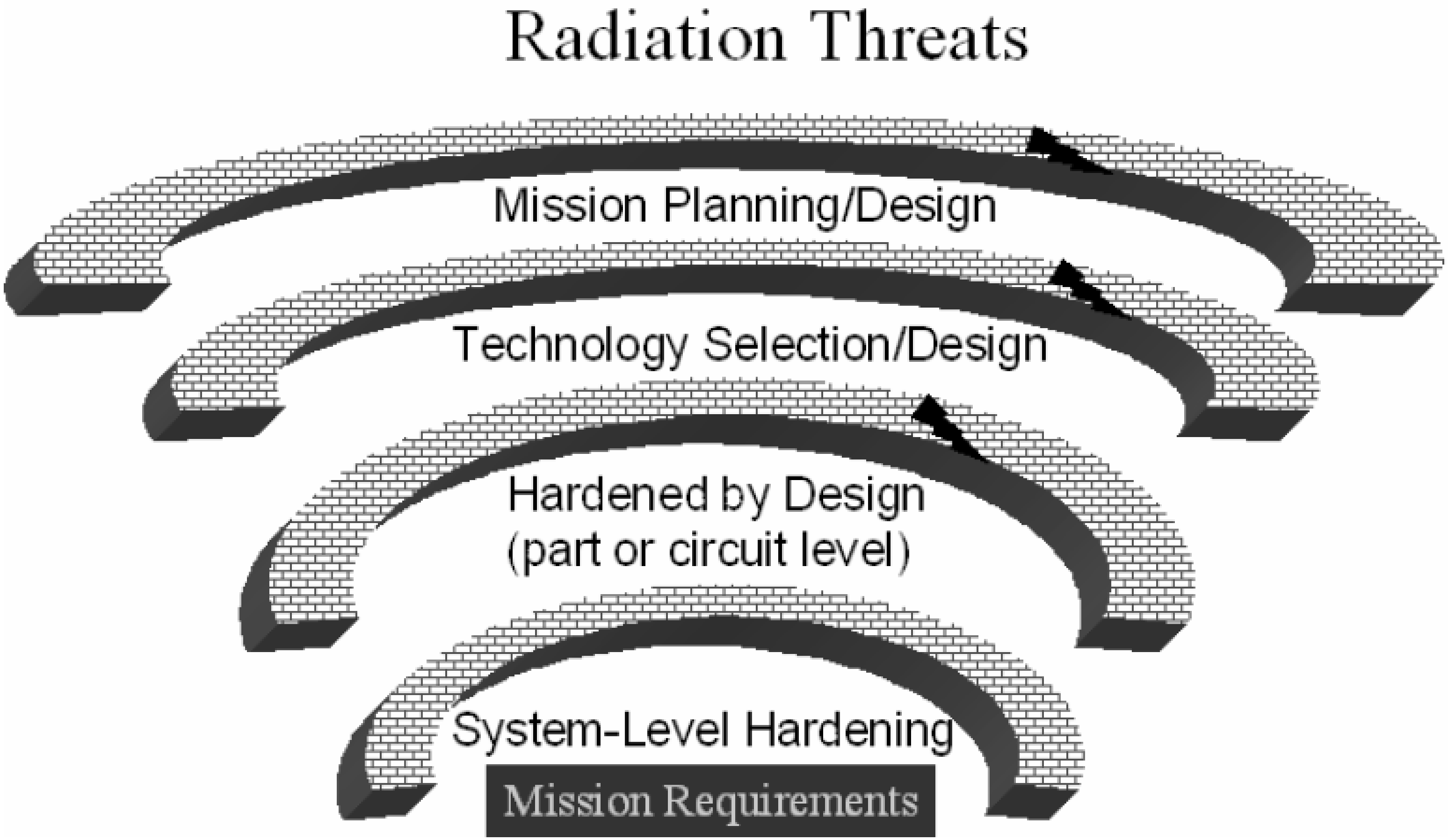


- To achieve mission performance one must balance
  - Technology
  - Cost
  - Schedule
- Most engineers tend to focus on technology – at the expense of cost and schedule
- Most programs tend to focus on cost and schedule – at the expense of technology

The trades between cost, schedule & technology define the level of risk

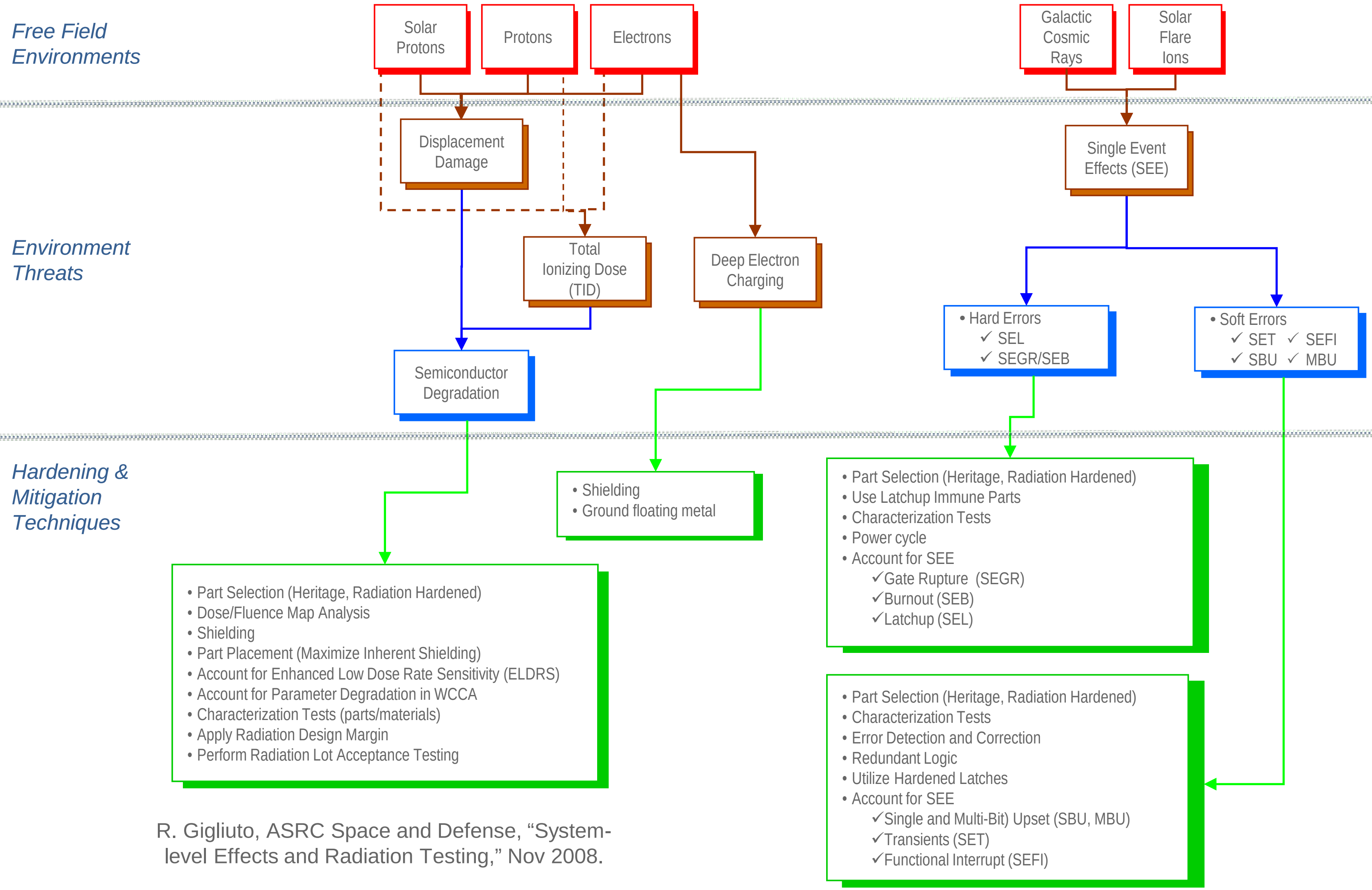
R. Gigliuto, ASRC Space and Defense, “System-level Effects and Radiation Testing,” Nov 2008.

Tiered defense strategy



R. L. Ladbury, IEEE NSREC Short Course, Jul 2007.

Environment design impacts

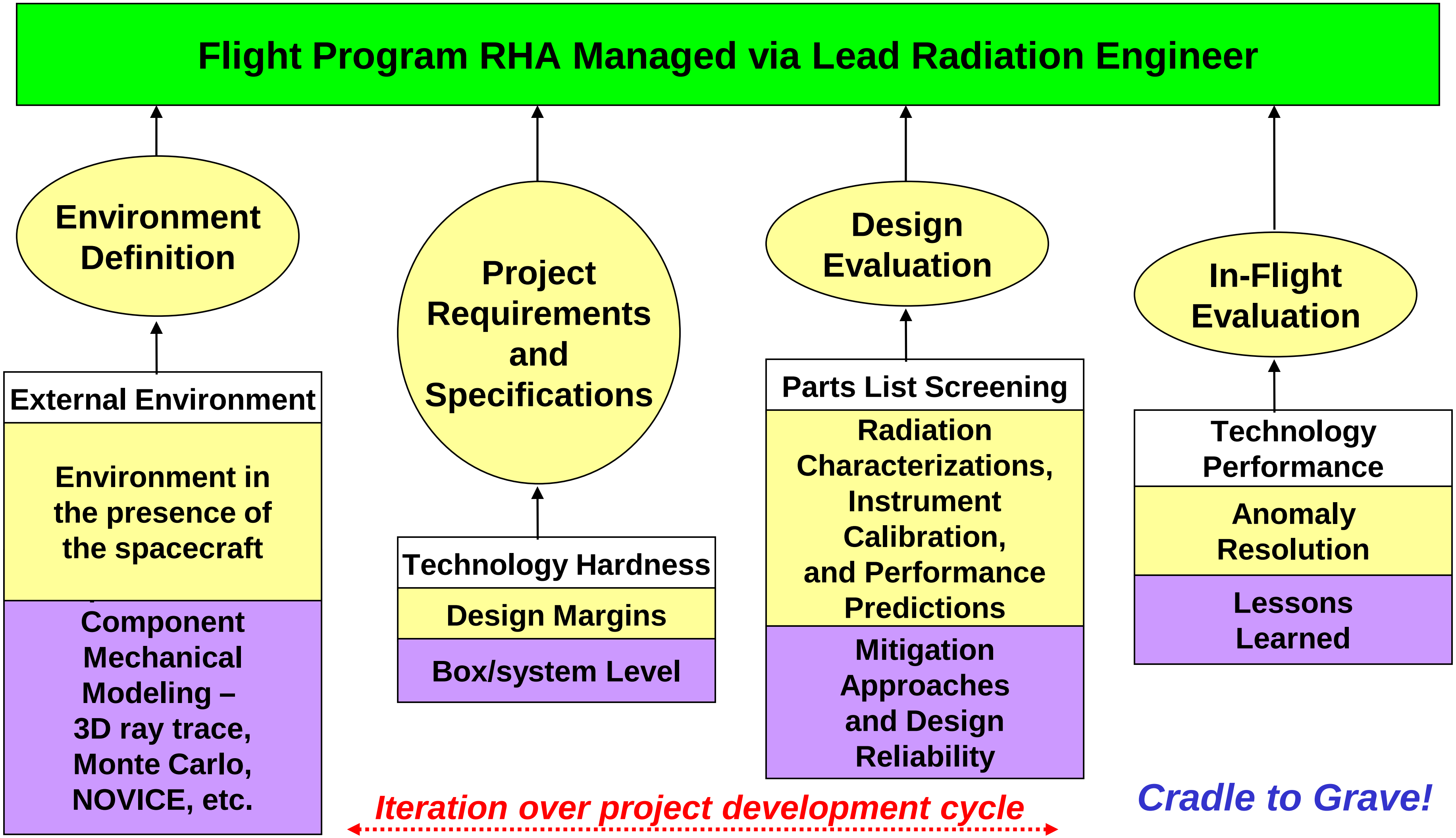


R. Gigliuto, ASRC Space and Defense, “System-level Effects and Radiation Testing,” Nov 2008.

Sensible Programmatics for Flight RHA: *A Two-Pronged Approach for Missions*

- Assign a lead radiation POC to each spaceflight project
  - Treat radiation like other engineering disciplines
    - Parts, thermal,...
  - Provides a single point of contact for all radiation issues
    - Environment, parts evaluation, testing,…
- Each program follows a systematic approach to RHA
  - Develop a comprehensive RHA plan
  - RHA active early in program reduces cost in the long run
    - Issues discovered late in programs can be expensive and stressful
      - What is the cost of reworking a flight board if a device has RHA issues?

RHA flow


Flight Program RHA Managed via Lead Radiation Engineer
Environment Definition
Project Requirements and Specifications
Design Evaluation
In-Flight Evaluation
External Environment
Environment in the presence of the spacecraft
Component Mechanical Modeling – 3D ray trace, Monte Carlo, NOVICE, etc.
Technology Hardness
Design Margins
Box/system Level
Parts List Screening
Radiation Characterizations, Instrument Calibration, and Performance Predictions
Mitigation Approaches and Design Reliability
Technology Performance
Anomaly Resolution
Lessons Learned
Iteration over project development cycle
Cradle to Grave!

Define the hazard

- The radiation environment external to the spacecraft
  - Trapped particles
    - Protons
    - Electrons
  - Galactic cosmic rays - GCRs (heavy ions)
  - Solar particles (protons and heavy ions)
- Based on
  - Time of launch and mission duration
  - Orbital parameters, …
- Provides as a minimum
  - GCR fluxes
  - Nominal and worst-case trapped particle fluxes
  - Peak “operate-through” fluxes (solar or trapped)
  - Dose-depth curve of total ionizing dose (TID)

Note: We are currently using static models for a dynamic environment

Evaluate the hazard

- Utilize mission-specific geometry to determine particle fluxes and TID at locations inside the spacecraft
  - 3-D ray trace (geometric sectoring)
- Typically multiple steps
  - Basic geometry (empty boxes,…) or single electronics box
  - Detailed geometry
    - Include printed circuit boards (PCBs), cables, integrated circuits (ICs), thermal louvers, etc…
- Usually an iterative process
  - Initial spacecraft design
  - As spacecraft design changes
  - Mitigation by changing box location

Define requirements

- Environment usually based on hazard definition with “nominal shielding” or basic geometry
  - Using actual spacecraft geometry sometimes provides a “less harsh” radiation requirement
- Performance requirements for “nominal shielding” such as 100 mil of Al or actual spacecraft configuration
  - TID
  - DDD (protons, neutrons)
  - SEE
    - Specification is more complex
- Inclusion of radiation design margin (RDM)
  - Factor of 2 for TID, for example
  - Often required to be higher due to device issues and environment uncertainties

System requirements

- For TID, parts can be given a single number (with margin)
  - SEE is much more application specific
- SEE is unlike TID
  - Probabilistic events, not long-term
    - For instance, equal probabilities for 1st day of mission or last day of mission
    - Requirements must be thoroughly defined – does it have to work, or would it be nice to have?

Notes on system requirements

- Requirements do NOT have to be for piece-part reliability
  - For example, may be viewed as a "data loss" specification
    - Acceptable bit error rates or system outage
  - Mitigation and risk are system trade parameters
  - Environment needs to be defined for *YOUR* mission (cannot use prediction for different timeframe, orbit, etc.)

Evaluate design and component usage

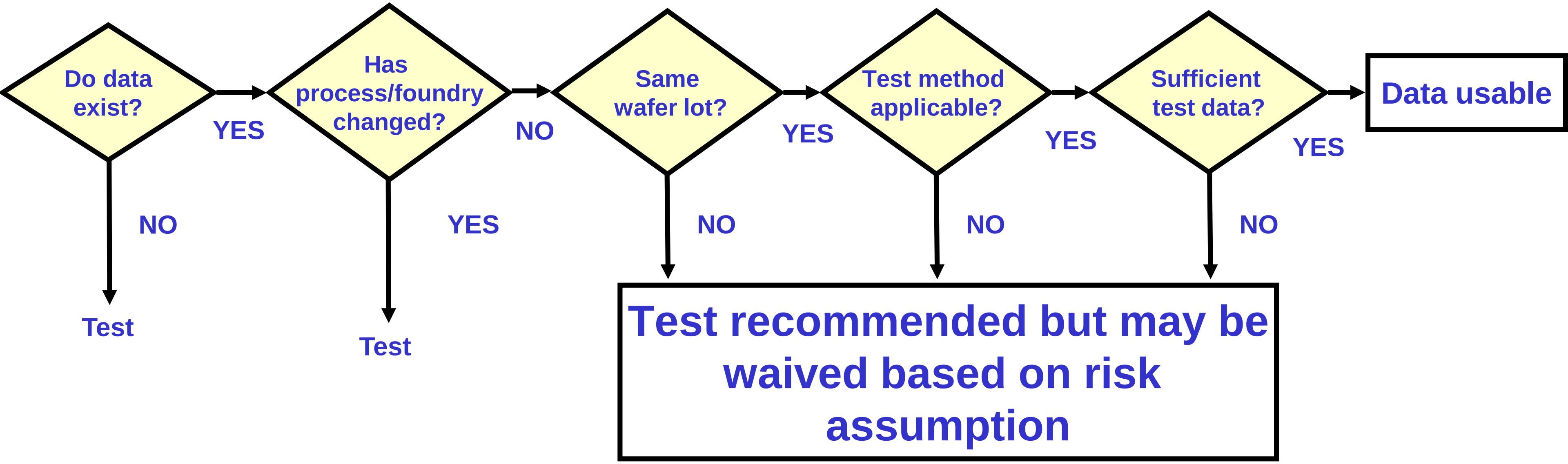
- Screen parts list
  - Use existing data sources
    - Evaluate test data: is it applicable?
    - Use historic data with CAUTION!
  - Look for processes or products with known radiation tolerance (beware of SEE and displacement damage!)
    - BAE Systems, Honeywell Solid State Electronics, Aeroflex, Intersil, etc.
- Radiation test unknowns or non-guaranteed devices
- Provide performance characteristics
  - Usually requires application-specific information: understand the designer's sensitive parameters
    - SEE rates
    - TID/DDD

Radiation perspective on IC selection

- From the radiation perspective, ICs can be viewed as part of one of four categories:
  - Guaranteed hardness
    - Radiation-hardened by process (RHBP)
    - Radiation-hardened by design (RHBD)
  - Historical ground-based radiation data
    - Lot acceptance criteria
  - Historical flight usage
    - Statistical significance
  - Unknown assurance
    - New device or one with no data or guarantee

Archival radiation performance – ground-based test data

- General flow is shown below



What does the radiation engineer need?

- The following is a list of information that should be provided to the radiation engineer to perform a scrub
  - Manufacturer
    - Note: QPL or QML are not manufacturers
  - Part number (generic)
  - SMD or Mil procurement number
    - RH designator?
  - Function
  - Lot date code
  - Technology of the part will drive what to look for in radiation test results and methods. You may have to dig up this information.
    - e.g., bipolar: was TID testing performed at low dose rate (per standards) or is the device “ELDRS-free”?
  - Application information may be required as well
    - 1st scrub can look at just what data is available
    - 2nd pass looks at applying that data

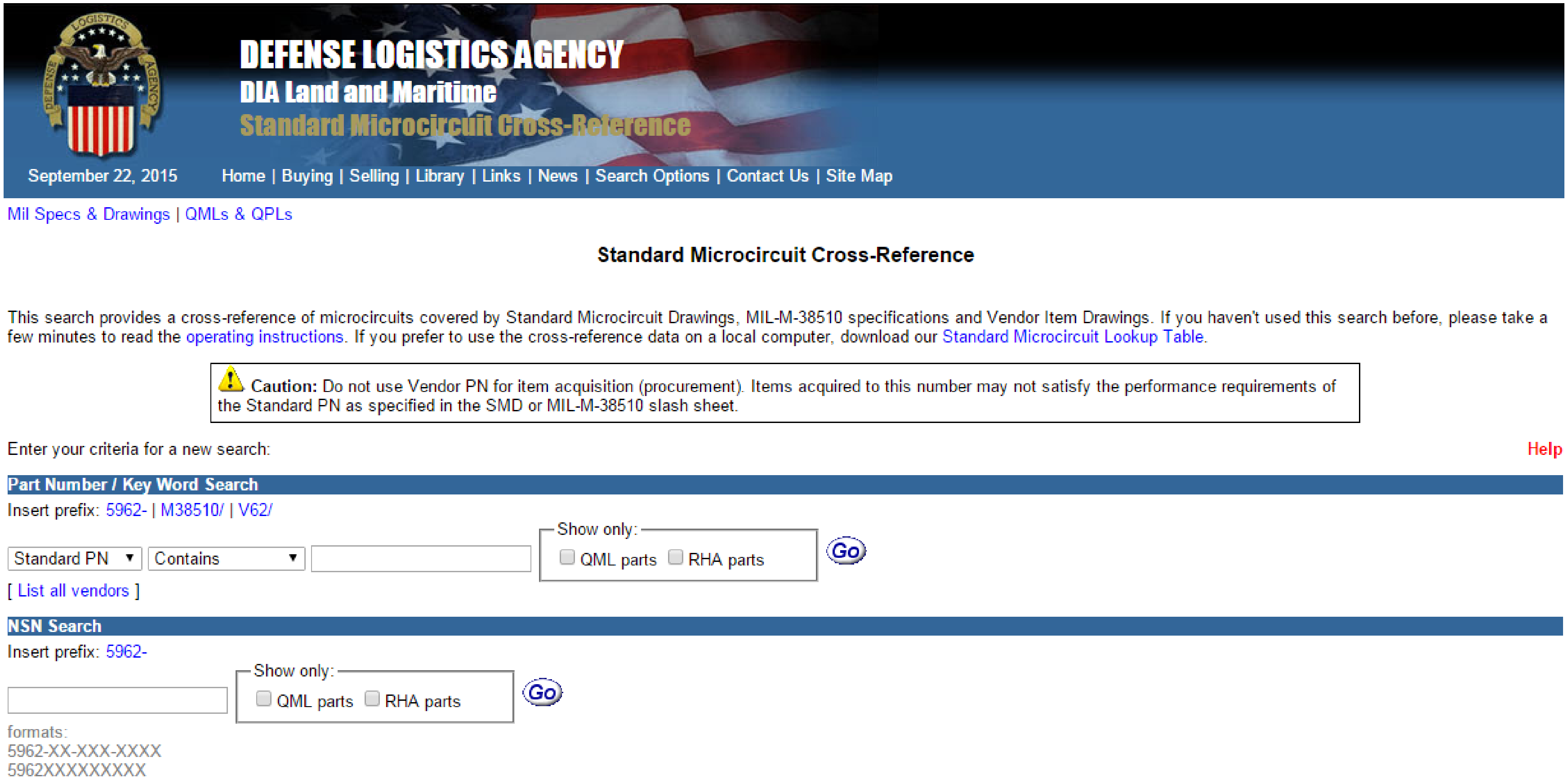
What the radiation engineer provides back to the project

- If the part is guaranteed for radiation
  - Feedback whether the guaranteed radiation tolerance meets mission requirements
    - Forewarning: not all guaranteed parts will meet a mission requirement or application
- If the part has ground test data available
  - Synopsis of the tolerance levels noted
    - Forewarning: many database radiation results are application-specific
      - Good results may be used as an indicator the part might be okay for selection, however, testing may be required
  - LDCs of the tested parts
    - Finding if it's the same wafer and lot as being considered is a challenge, but unless it's a known lot that's being purchased, radiation qualification testing is often required
  - Testing recommendations based on requirements and part technology
  - Replacement recommendations
- If the part does not have data
  - Is there data on the process?
  - Is there data on a similar or more complex part on the same process?
- Flight heritage will be discussed later
- Beyond just the data, SEE rate predictions for the mission may be included as well

What can be on a parts list

- Military and procurement specs are often found on parts lists. These may be in the form of:
  - SMD
    - Standard Microcircuit Drawing
      - There may also be Mil-38510 or vendor drawings
  - QPL
    - Qualified Parts List
  - QML
    - Qualified Manufacturers List
  - RHA
    - Radiation Hardened Assurance (RHA). This refers to the RHA designator for total ionizing dose (TID) only. Single event effects (SEE) are NOT guaranteed by the RHA designator as a rule.
- DLA Land & Maritime Standard Microcircuit Cross-Reference
  - http://www.dscc.dla.mil/programs/smcr/
  - Website and downloadable tools are useful in translating generic part numbers to/from military part numbers
- Other generic component information

Microcircuit cross reference



DEFENSE LOGISTICS AGENCY
DLA Land and Maritime
Standard Microcircuit Cross-Reference

September 22, 2015 Home | Buying | Selling | Library | Links | News | Search Options | Contact Us | Site Map

Mil Specs & Drawings | QMLs & QPLs

Standard Microcircuit Cross-Reference

This search provides a cross-reference of microcircuits covered by Standard Microcircuit Drawings, MIL-M-38510 specifications and Vendor Item Drawings. If you haven't used this search before, please take a few minutes to read the operating instructions. If you prefer to use the cross-reference data on a local computer, download our Standard Microcircuit Lookup Table.

Caution: Do not use Vendor PN for item acquisition (procurement). Items acquired to this number may not satisfy the performance requirements of the Standard PN as specified in the SMD or MIL-M-38510 slash sheet.

Enter your criteria for a new search: Help

Part Number / Key Word Search

Insert prefix: 5962- | M38510/ | V62/

Standard PN | Contains | Show only: QML parts RHA parts | Go

[List all vendors]

NSN Search

Insert prefix: 5962-

Show only: QML parts RHA parts | Go

formats:
5962-XX-XXX-XXXX
5962XXXXXXXXX

Sample SMD - memory

1. SCOPE

1.1 Scope. This drawing documents two product assurance class levels consisting of high reliability (device class Q) and space application (device class V). A choice of case outlines and lead finishes are available and are reflected in the Part or Identifying Number (PIN). When available, a choice of Radiation Hardness Assurance (RHA) levels are reflected in the PIN.

1.2 PIN. The PIN shall be as shown in the following example:

5962	R	10203	01	Q	X	A
Federal stock class designator	RHA designator (see 1.2.1)		Device type (see 1.2.2)	Device class designator (see 1.2.3)	Case outline (see 1.2.4)	Lead finish (see 1.2.5)

\ ________________ ________________ /
V
Drawing number

1.2.1 RHA designator. Device classes Q and V RHA marked devices shall meet the MIL-PRF-38535 specified RHA levels and are marked with the appropriate RHA designator. A dash (-) indicates a non-RHA device.

1.2.2 Device types. The device types shall identify the circuit function as follows:

Device type	Generic number	Circuit function	Access time
01	UT8ER2M32M	2M X 32-bit rad-hard SRAM master	22 ns
02	UT8ER2M32S	2M X 32-bit rad-hard SRAM slave	22 ns
03	UT8ER2M32M	2M X 32-bit rad-hard SRAM master, with additional screening 1/	22 ns
04	UT8ER2M32S	2M X 32-bit rad-hard SRAM slave, with additional screening 1/	22 ns

1.2.3 Device class designator. The device class designator shall be a single letter identifying the product assurance level as follows:

Device class	Device requirements documentation
Q, V	Certification and qualification to MIL-PRF-38535

Monolithic RHA

4.4.4 Group E inspection. Group E inspection is required only for parts intended to be marked as radiation hardness assured (see 3.5 herein). RHA levels for device classes Q and V shall be as specified in MIL-PRF-38535 and the end-point electrical parameters shall be as specified in Table IIA herein.

a. For device classes Q and V, the devices or test vehicle shall be subjected to radiation hardness assured tests as specified in MIL-PRF-38535 for the RHA level being tested. All device classes must meet the post-irradiation end-point electrical parameter limits as defined in Table IA at T_A = +25°C ±5°C, after exposure, to the subgroups specified in Table IIA herein.

4.4.4.1 Total dose irradiation testing. Total dose irradiation testing shall be performed in accordance with MIL-STD-883 method 1019 condition A, and as specified herein. The total dose requirements shall be as defined within paragraph 1.5 herein.

4.4.4.1.1 Accelerated annealing test. Accelerated annealing tests shall be performed on all devices requiring a RHA level greater than 5k rads(Si). The post-anneal end-point electrical parameter limits shall be as specified in Table IA herein and shall be the pre-irradiation end-point electrical parameter limit at 25°C ±5°C. Testing shall be performed at initial qualification and after any design or process changes which may affect the RHA response of the device.

4.4.4.2 Dose rate induced latch-up testing. When specified by the procuring activity, dose rate induced latch-up testing shall be performed in accordance with method 1020 of MIL-STD-883 and as specified herein (see 1.5). Tests shall be performed on devices, SEC, or approved test structures at technology qualification and after any design or process changes which may effect the RHA capability of the process.

4.4.4.3 Dose rate upset testing. When specified by the procuring activity, dose rate upset testing shall be performed in accordance with method 1021 of MIL-STD-883 and herein (see 1.5).

a. Transient dose rate upset testing shall be performed at initial qualification and after any design or process changes which may affect the RHA performance of the devices. Test 10 devices with 0 defects unless otherwise specified.

b. Transient dose rate upset testing for class Q and V devices shall be performed as specified by a TRB approved radiation hardness assurance plan and MIL-PRF-38535.

4.4.4.4 Single event phenomena (SEP). When specified in the purchase order or contract, SEP testing shall be required on class V devices (see 1.5 herein). SEP testing shall be performed on a technology process on the Standard Evaluation Circuit (SEC) or alternate SEP test vehicle as approved by the qualifying activity at initial qualification and after any design or process changes which may affect the upset or latchup characteristics. ASTM standard F1192 may be used as a guideline when performing SEP testing. The recommended test conditions for SEP are as follows:

a. The ion beam angle of incidence shall be between normal to the die surface and 60° to the normal, inclusive (i.e. 0° ≤ angle ≤ 60°). No shadowing of the ion beam due to fixturing or package related effects are allowed.

b. The fluence shall be ≥ 100 errors or ≥ 10^6 ions/cm^2.

c. The flux shall be between 10^2 and 10^5 ions/cm^2/s. The cross-section shall be verified to be flux independent by measuring the cross-section at two flux rates which differ by at least an order of magnitude.

d. The particle range shall be ≥ 20 microns in silicon.

e. The test temperature shall be +25°C ±10°C for single event upset testing and at the maximum rated operating temperature ±10°C for single event upset testing.

f. Bias conditions shall be defined by the manufacturer for latchup measurements.

g. Test four devices with zero failures.

Sample SMD - hybrid

1. SCOPE

1.1 Scope. This drawing documents five product assurance classes as defined in paragraph 1.2.3 and MIL-PRF-38534. A choice of case outlines and lead finishes which are available and are reflected in the Part or Identifying Number (PIN). When available, a choice of radiation hardness assurance levels are reflected in the PIN.

1.2 PIN. The PIN shall be as shown in the following example:

```
   5962              -           98529        01          H            X           X
    |                |                         |          |            |           |
 Federal            RHA                      Device     Device        Case        Lead
 stock class     designator                   type       class       outline     finish
 designator      (see 1.2.1)               (see 1.2.2) designator  (see 1.2.4) (see 1.2.5)
 \_______________________________/                     (see 1.2.3)
                 V
          Drawing number
```

1.2.1 Radiation hardness assurance (RHA) designator. RHA marked devices shall meet the MIL-PRF-38534 specified RHA levels and shall be marked with the appropriate RHA designator. A dash (-) indicates a non-RHA device.

1.2.2 Device type(s). The device type(s) identify the circuit function as follows:

Device type	Generic number	Circuit function
01	SLH2815D	DC-DC converter, 1.5 W, ±15V outputs

1.2.3 Device class designator. This device class designator shall be a single letter identifying the product assurance level. All levels are defined by the requirements of MIL-PRF-38534 and require QML Certification as well as qualification (Class H, K, and E) or QML Listing (Class G and D). The product assurance levels are as follows:

Device class	Device performance documentation
K	Highest reliability class available. This level is intended for use in space applications.
H	Standard military quality class level. This level is intended for use in applications where non-space high reliability devices are required.

Hybrid RHA

4.3.5. Radiation hardness assurance (RHA). RHA qualification is required only for those devices with the RHA designator as specified herein.

	RHA level L	RHA level R	Units
Total ionizing dose tolerance level	50	100	kRad (Si)
Single event upset survival level (LET)	No guarantee	40	MeV

a. Radiation dose rate is in accordance with condition C of method 1019 of MIL-STD-883. Unless otherwise specified, components are tested at a rate of 9 rad(Si)/s, in accordance with method 1019 of MIL-STD-750 or MIL-STD-883, as applicable. These parts may be dose rate sensitive in a space environment and may demonstrate enhanced low dose rate effects.

b. The manufacturer shall perform a worst-case and radiation susceptibility analysis on the device. This analysis shall show that the minimum performance requirements of each component has adequate design margin under worst-case operating conditions (extremes of line voltage, temperatures, load, frequency, radiation environment, etc.). This analysis guarantees the post-irradiation parameter limits specified in table I.

c. RHA testing shall be performed at the component level for initial device qualification, and after design changes that may affect the RHA performance of the device. As an alternative to testing, components may be procured to manufacturer radiation guarantees that meet the minimum performance requirements. Component radiation performance guarantees shall be established in compliance with MIL-PRF-19500, Group D or MIL-PRF-38535, Group E, as applicable. For components with less than adequate performance margin, component lot radiation acceptance screening shall be performed.

d. The manufacturer shall establish procedures controlling component radiation testing, and shall establish radiation test plans used to implement component lot qualification during procurement. Test plans and test reports shall be filed and controlled in accordance with the manufacturer's configuration management system.

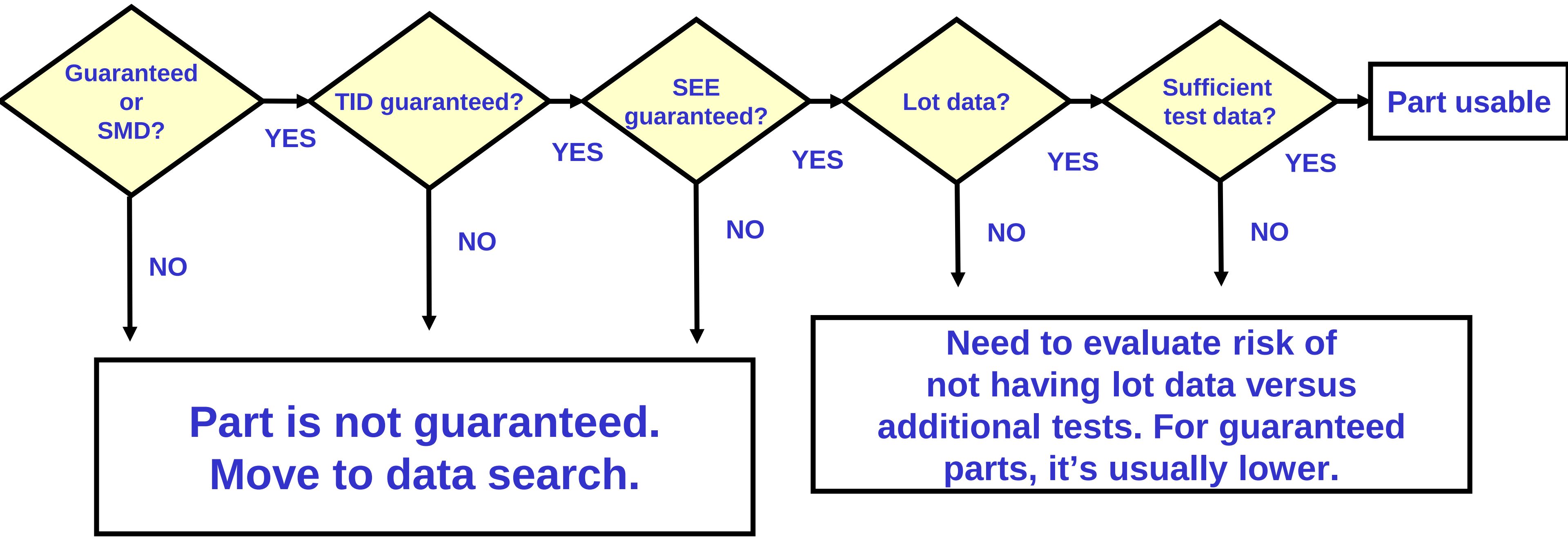
e. The device manufacturer shall designate a RHA program manager to oversee component lot qualification, and to monitor design changes for continued compliance to RHA requirements.

Guaranteed radiation tolerance

- So, we've started perusing the review of parts guaranteed by the vendor using the MIL system
  - Now let's move on to a bit more detail
- A limited number of semiconductor manufacturers, either with fabs or fabless, will guarantee radiation performance of devices
  - Examples:
    - ATMEL, Honeywell, BAE Systems, Aeroflex, etc.
  - Radiation qualification usually is performed on either:
    - Qualification test vehicle,
    - Device type or family member, or
    - Lot qualification
  - Some vendors sell "guaranteed" radiation tolerant devices by "cherry-picking" commercial devices coupled with mitigation approaches external to the die
- The devices themselves can be hardened via
  - Process or material (RHBP or RHBM),
  - Design (RHBD), or
  - Serendipity (RHBS)
- Most foundries use a combination of techniques

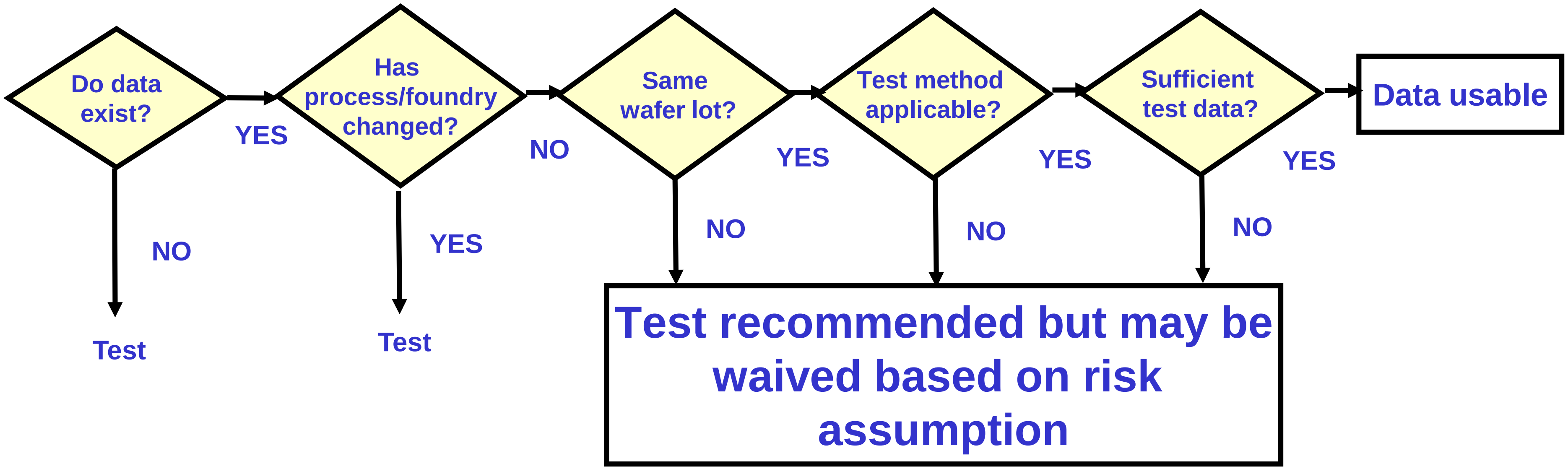
Evaluating "guaranteed" parts

- Even guaranteed parts may have issues
  - For both TID and SEE?
  - Lot testing requirements
  - Application-specific issue (how was the qualification done?)
  - What about ELDRS if testing was done at high dose rate?



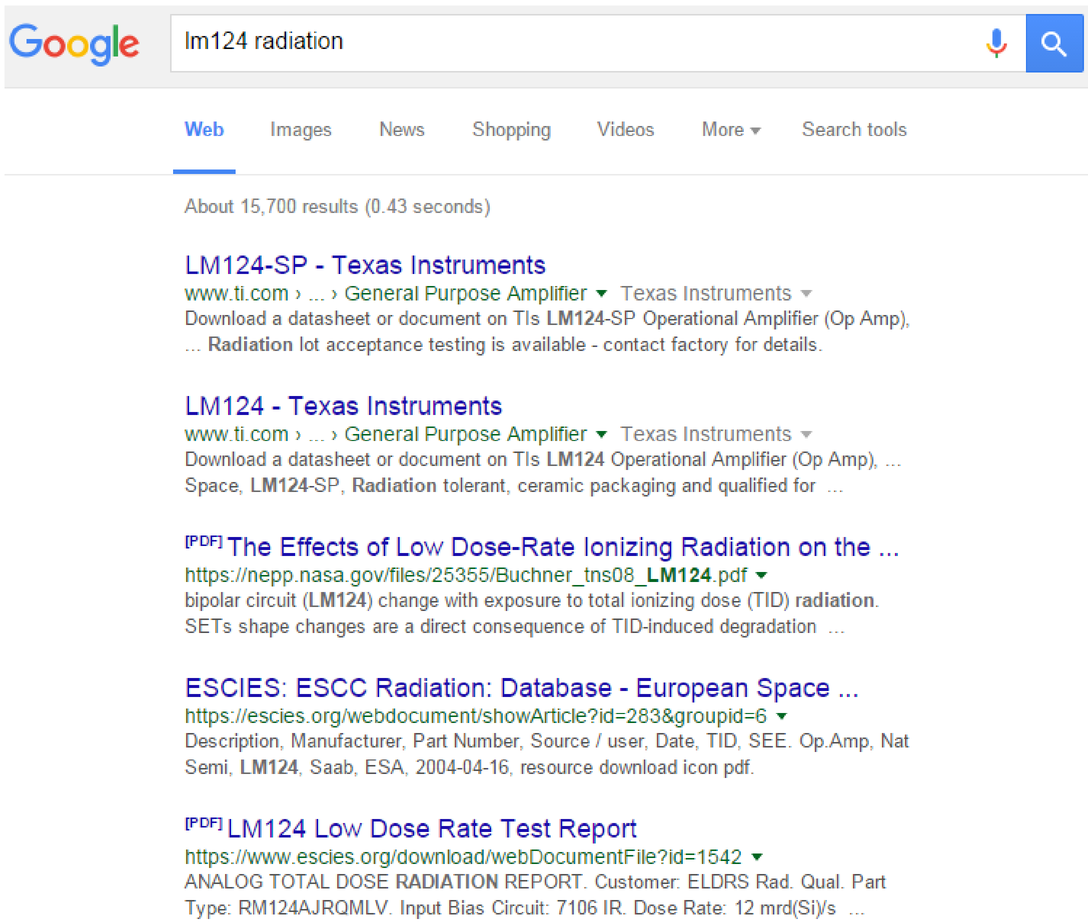
Ground-based data

- Once we have determined if the part is guaranteed or not, we begin searching for available data
  - Note: using a “similar” device with data is risky, but sometimes considered (though not recommended)
    - This is known as “qual by similarity”
- We can consider “heritage” from other programs/projects, but this is risky too



Data searches…

- Why not try Google?



Archival radiation performance – heritage data

- Can we make use of parts with flight heritage and no ground data for new mission?
- Similar flow to using archival ground data exist, but consider:
  - Statistical significance of the flight data
    - Environment severity?
    - Number of samples?
    - Length of mission?
    - e.g., 1 part flying for 3 years in a LEO orbit doesn't mean much on a 10-year mission to Mars!
  - Has storage of devices affected radiation tolerance or reliability?
- This approach is rarely recommended by the radiation expert

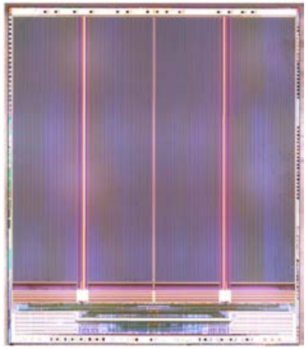
Some heritage designs last better than others

Components with no guarantee or heritage

- Radiation testing is required in the vast majority of cases
  - Challenge is to gather sufficient data in a cost and schedule effective manner
    - » A backup plan should be made in case device fails to pass radiation criteria.
- Hard question is when do we need to test
  - Consider:
    - » Mission parameters
    - » Application/operation
    - » Process and device family knowledge
  - In some cases, we can estimate “worst-case,” such as transient size

Is testing always required?

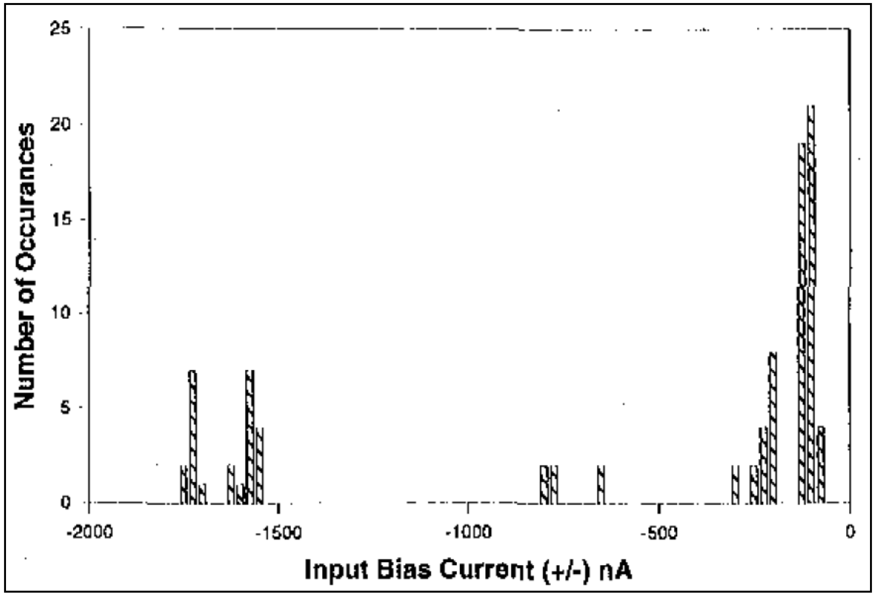
- Exceptions for testing may include
  - Operational
    - Example: device is only powered on once per orbit and the sensitive time window for a single event effect is minimal
  - Acceptable data loss
    - Example: system-level error rate may be set such that data are gathered 95% of the time. Given physical device volume and assuming every ion causes an upset, this worst-case rate may be tractable.
  - Negligible effect
    - Example: 2 week mission to LEO may have a very low TID requirement. TID testing could be waived.



FLASH memory may be acceptable without testing if a low TID requirement exists or not powered on for the large majority of time.

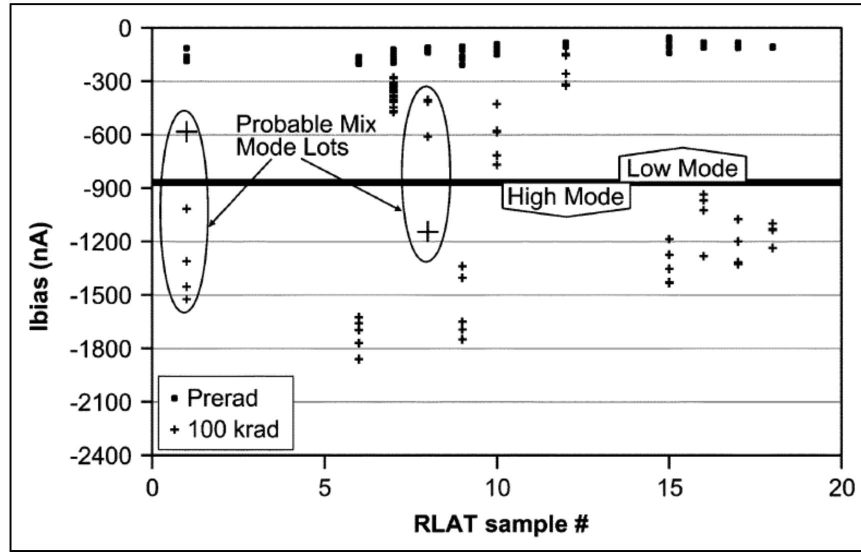
Why lot-based qualification testing?

LM111 Voltage Comparator at 50 krad(SiO_2)



J. Krieg, *et al.*, *IEEE TNS*, 1999.

OP484 Quad Op Amp at 100 krad(SiO_2)

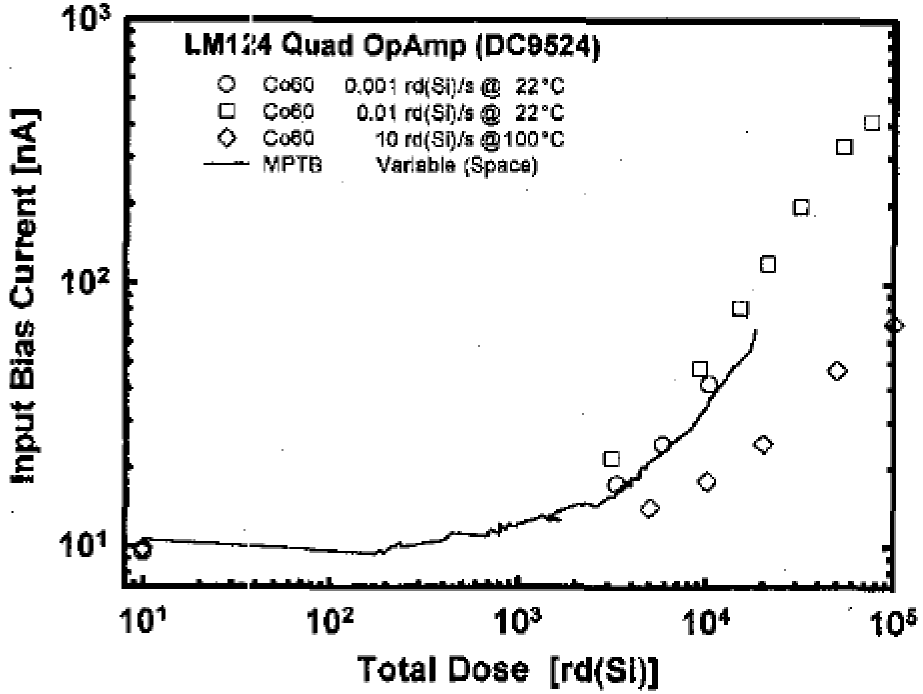


R. Ladbury, *et al.*, *IEEE TNS*, 2005.

- Components used are illustrative – many examples exist
- Bimodality complicates analysis and limits confidence

Other complexities too…

- Dose rate dependence is just one aspect
- Could also consider operating frequency effects, bias, temperature, ion species, etc.



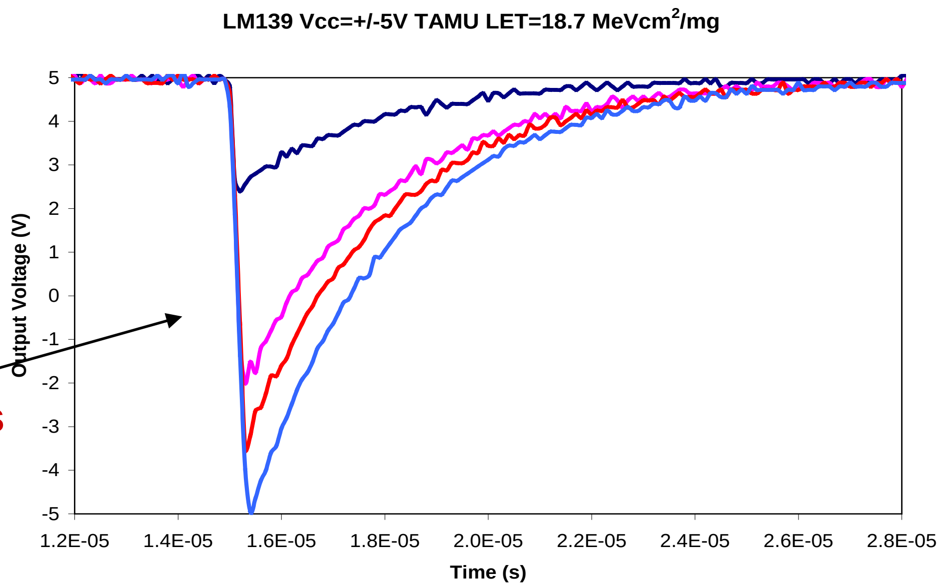
J. L. Titus, et al., *IEEE Trans. Nucl. Sci.*, vol. 46, Dec. 1999.

Data applicability – Example 1

- Most SEE data available is application-specific
  - o Power supply voltages
  - o Operating frequency
    - » Fidelity of response measured

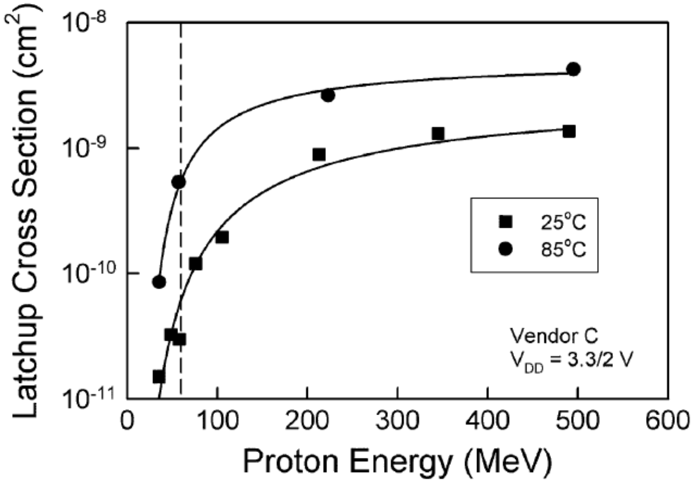
      Was the scope fast enough to capture "small" transients that might perturb sensitive data?
  - o Circuit load
  - o Test patterns
  - o Temperature
  - o Bias configuration

Transients in a linear device can vary with input parameters



Data applicability – Example 2

- SRAM used in a solid state recorder (SSR)
  - SEE ground test data may have been in dynamic mode with a 1 MHz operating frequency
  - Application may be quasi-static
    - Write once an orbit (collect data)
    - Read once an orbit (downlink data)
  - There is often a duty cycle effect for SEE sensitivity
    - Device may be more or less sensitive in a quasi-static mode of operation
  - Device may also have a prevalence of 0-1 vs. 1-0 upset
    - Implies SEU sensitivity is a function of data patterns
    - If test pattern is all 1's or all 0s, data may not be applicable
    - Hitachi 1 Mbit SRAM was 49X more sensitive in one direction than the other!



Effect of temperature on SEE sensitivity

J. R. Schwank, et al., *IEEE Trans. Nucl. Sci.*, vol. 52, no. 6, Dec. 2005.

Risk is the name of the game

- **Rule**: there will always be risks associated with any use of electronics in a space radiation environment
  - We try to minimize and to determine what is reasonable
- Lot-specific information and guaranteed devices ARE the best choices
  - Risk is usually being assumed at all other times
  - Historical performance can be an indicator for usage, but is fraught with risk
    - How much is a judgment call based on available information?
    - It is your job to dig for the info and make a recommendation?

Levels of mitigation

- Mitigation can take place at many levels
  - Operational
    - No operation in SAA (proton hazard)
  - System
    - Redundant boxes/buses
  - Circuit/software
    - Error detection and correction (EDAC) scrubbing of memory devices by external device or processor
  - Device
    - Triple-modular redundancy (TMR) of internal logic
  - Transistor
    - Use of annular transistors for TID improvement
  - Material
    - Addition of an epitaxial substrate to reduce SEE charge collection (or other substrate engineering)
- Good engineers can invent infinite solutions, but…

Mitigation for destructive effects

- Do not use devices that exhibit destructive conditions in your environment and application
  - o Difficulties:
    - » May require redundant components/systems
    - » Conditions such as low current SELs may be difficult to detect
- Mitigation methods
  - o Current limiting
  - o Current limiting with autonomous reset
  - o Periodic power cycles
  - o Device functionality checks
- Latent damage is also a grave issue
  - o “Non-destructive” events may be a false statement
  - o All devices that have SEL sensitivity even with circumvention circuits need to consider this

Takeaways

- Systematic approach is a must
- Coordinate with relevant parties (e.g., system engineer, parts engineer, etc.)
- Use all available data sources
- Don’t be afraid to ask if you don’t know
  - Don’t go forward without expertise
  - Don’t throw it over the fence completely
- Hopefully track successful performance in-flight
  - Invaluable for future efforts

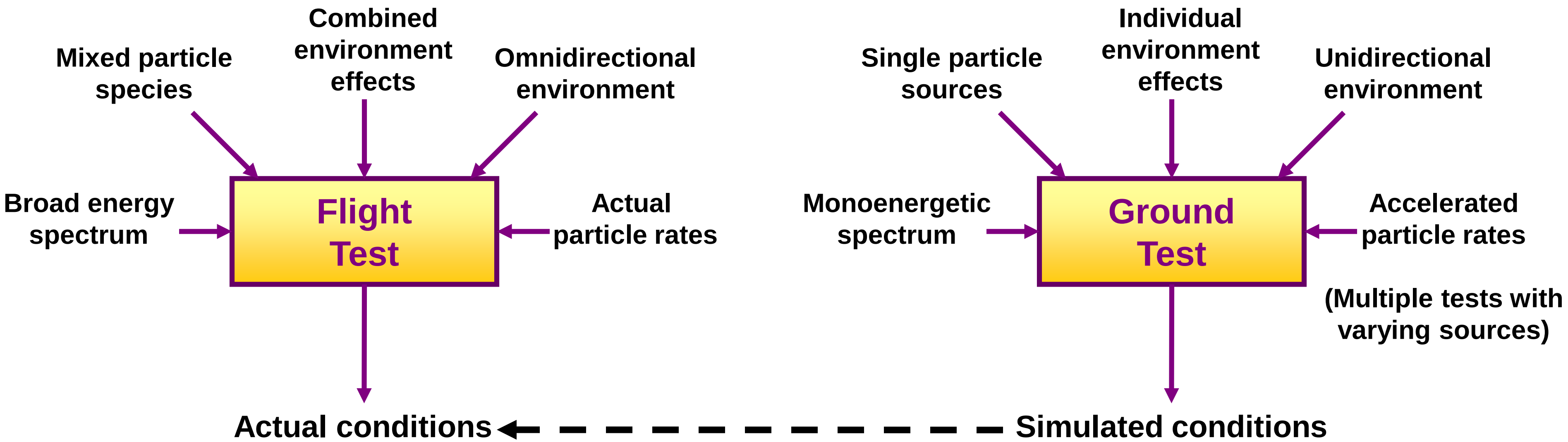
Course sections

1. Introduction
2. Natural space radiation environment
3. Space environment impacts
4. Component selection and radiation effects mitigation
5. **Radiation testing**
6. Conclusion

RADIATION TESTING –

Back the flux off!

Radiation test fidelity



How accurate is the ground test in predicting Space Performance?

After graphic prepared by K. A. LaBel, NASA GSFC, 2008.

Landscape is always changing…

The missing memristor found

D. B. Strukov, *et al., Nature*, vol. 453, pp. 80-83, May 2008.

IEF2011: HP to replace flash and SSD in 2013

David Manners
Thursday 06 October 2011 12:17

HP intends to have an alternative technology to flash on the market in eighteen months, an alternative to DRAM in three to four years and, following DRAM, a replacement for SRAM, Stan Williams, Senior Fellow at HP, told the IEF2011 meeting in Seville this morning.

"We're planning to put a replacement chip on the market to go up against flash within a year and a half," said Williams, "and we also intend to have an SSD replacement available in a year and a half."

"In 2014 possibly, or certainly by 2015, we will have a competitor for DRAM and then we'll replace SRAM."

http://www.electronicsweekly.com/Articles/06/10/2011/51988/ief2011-hp-to-replace-flash-and-ssd-in-2013.htm

DDR4 makes its debut at ISSCC 2012

Servers in 2013, desktops the coming year

23 Feb 2012 18:47 | by Paul Taylor in Lisbon | Filed in Chips Samsung DDR3

http://news.techeye.net/chips/ddr4-makes-its-debut-at-isscc-2012

Tuesday, Feb. 28, 2012

Chip maker falls to yen, Asian rivals

Elpida seeks bankruptcy protection

Kyodo, Bloomberg

Struggling semiconductor maker Elpida Memory Inc. filed for bankruptcy protection Monday after giving up on efforts to rebuild itself with government support.

http://www.japantimes.co.jp/text/nb20120228n1.html

Where we're going…

THEN	**NOW**
Magnetic core memory	**NAND flash, resistive random access memory (RAM), magnetic RAM, phase-change RAM, programmable metallization cell RAM, and double-data rate (DDR) synchronous dynamic RAM (SDRAM)**
Single-bit upsets (SBUs) and single-event transients (SETs)	**Multiple-bit upset (MBU), block errors, single-event functional interrupts (SEFIs), frequency-dependence, *etc*.**
Heavy ions and high-energy protons	**Heavy ions, high- and low-energy protons, delta rays, muons, ???**
Radiation hardness assurance (RHA)	**RHA what?**

Where we're going…

THEN	NOW

Increases in capability introduce additional evaluation challenges

- FinFETs/Tri-gate devices
- Nanowire MOSFETs
- Organic transistors
- Ultra-thin body SOI
- Ge MOSFETs
- III-V MOSFETs
- Carbon nanotube FETs
- GaN, SiC,…

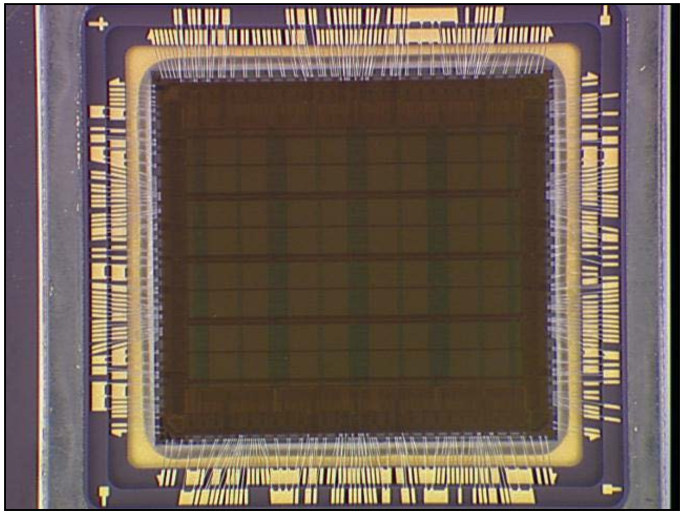
TESTABILITY

Two general types of electronics for space use

- Commercial-off-the-shelf (COTS) electronics
  - o Designed with no attempt to mitigate radiation effects. COTS can refer to commodity devices or to application-specific integrated circuits (ASICs) designed using a commercially available system.
- Radiation-tolerant electronics
  - o Designed explicitly to account for and mitigate radiation effects by process and/or design

K. Kohnen and K. Chestnut, *IEEE NSREC Short Course*, 2009.

http://www.samsung.com/us/computer/memory-storage/MV-3T4G3/US



Antifuse field programmable gate array

Evaluation of Total Ionizing Dose in Advanced Electronics – *Tolerance has gotten better, but device complexity increases faster*

Piece part hardness assurance

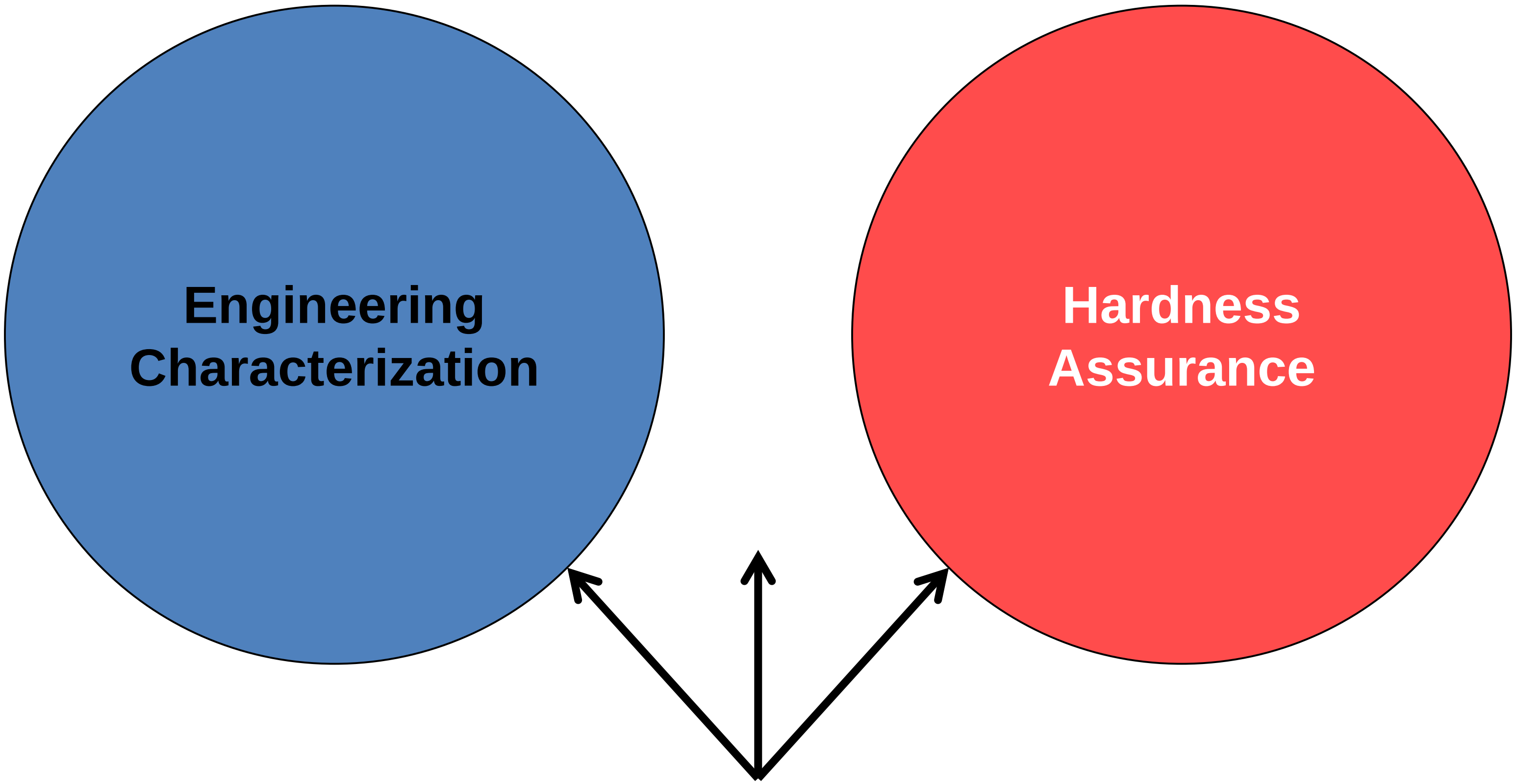
- We define piece-part hardness assurance as “the methods used to assure that microelectronic piece-parts meet specified requirements for system operation at specified radiation levels for a given probability of survival (P_S) and level of confidence (C)”.
  - Using this definition allows us to quantify the process.
  - Requirement for system operation allows for a failure definition that is determined by the application of the part in the system.
  - Requirement to meet a specified radiation level allows us to test parts as a function of a radiation environment and compare the radiation failure level of the part to the specification level.
  - Finally the specification of the P_S and C for the part will allow us to develop statistical approaches for sample testing of the parts.

R. L. Pease, *IEEE NSREC Short Course*, 2004.

Characterization *vs* qualification

- Engineering characterization test
  - Measuring device/material characteristics under the influence of an externally-imposed radiation environment stimulus
  - Not a “yes / no” answer
  - May be appropriate when: don’t know performance *a priori*, have limited samples, requirements are not well-defined
- Hardness assurance test
  - Test to assure requirements are met
  - “Yes / no” answer
  - Tends to imply statistical rigor – beware though

How do you approach radiation testing advanced electronics?



Radiation testing protocols for advanced electronics

Common TID testing themes

- Difficulty of in-situ evaluation
  - “Test as you fly” implies application realism – maybe not the best approach
- Component complexity creates “black boxes”
  - Does my test lack sensitivity/specificity?
  - Could refer to discrete devices or integrated circuits
- Component material systems now comprise most of the periodic table (equilibrium, dose enhancement,…)
- Existing test methods for bounding predictions rely on well-behaved results and controlled starting materials
  - Bimodal degradation/failure distributions
  - Part-to-part and lot-to-lot variability of commercial devices

“Lot” can be defined as the manufacturing or wafer/diffusion lot depending on context.

TID testing

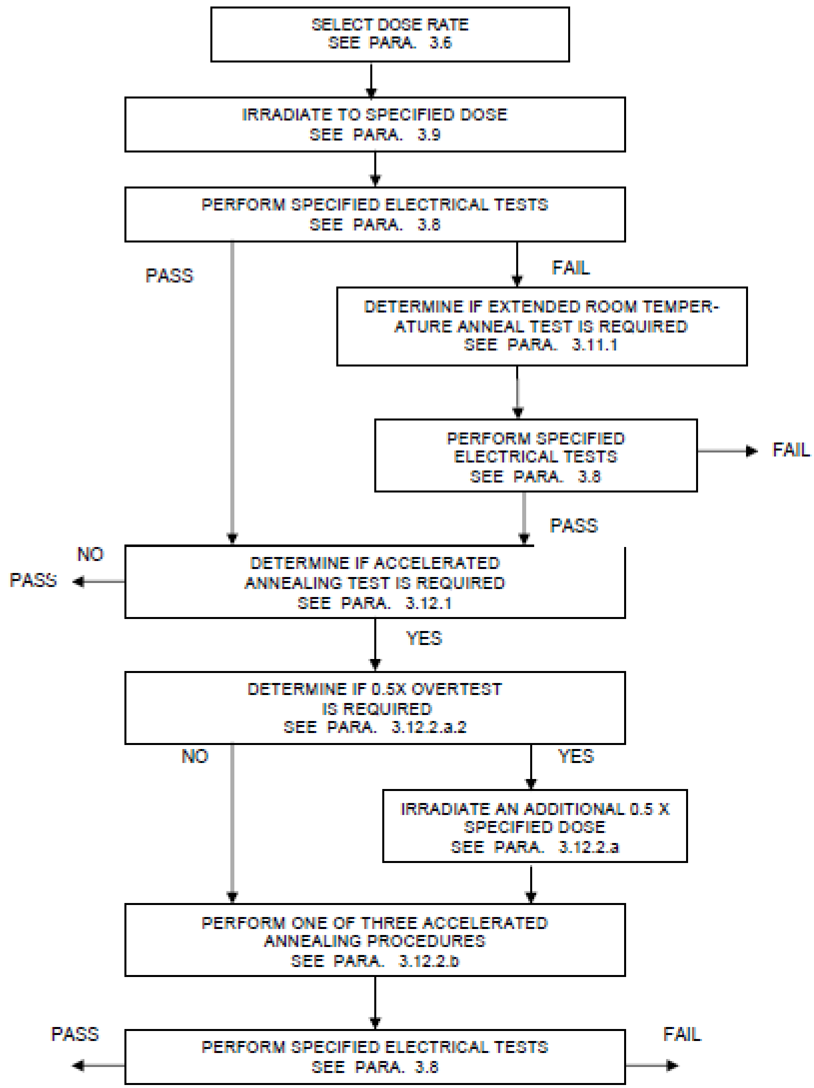
- Why do TID testing?
  - To determine the type and magnitude of parametric degradation and check for functional failures
  - To calculate the suitability for a radiation environment
- TID testing is carried out with an ionizing radiation source
  - Photons: ^{60}Co, ^{137}Cs, and ARACOR X-ray sources
  - Electrons: LINAC and Van de Graaff accelerators
  - Protons: cyclotron and Van de Graaff accelerators
- Limited device preparation required in most cases

Available TID test methods

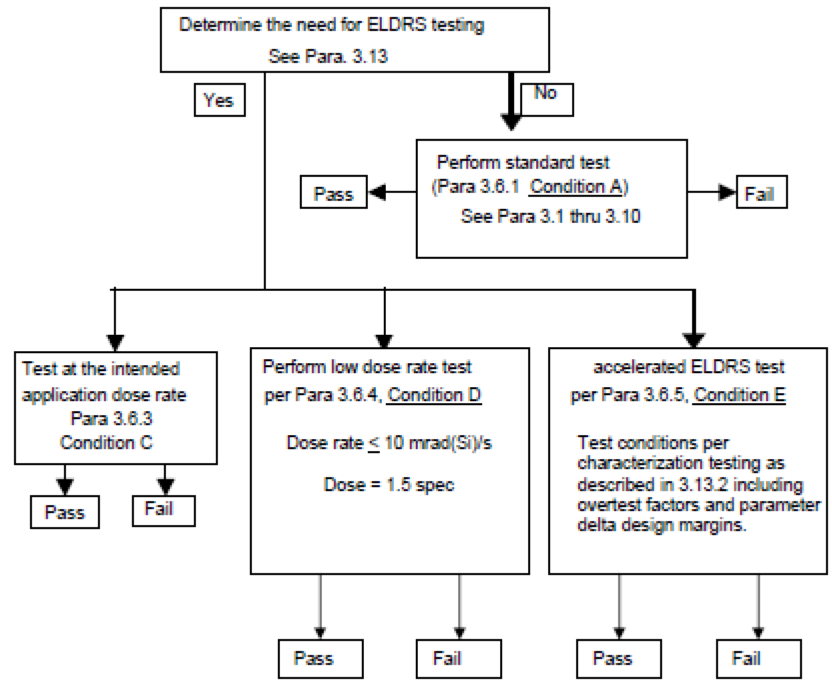
- Qualification methods that define total ionizing dose testing of microelectronics *(last update):*
  - MIL-STD-883, Method 1019 (06/2013)
  - ESCC Basic Specification No. 22900 (10/2010)
- Specific methods cover radiation hardness assurance – this is *qualification*
  - Can be adapted for engineering characterization
- Both of the above methods have procedures to test for and measure enhanced low-dose-rate sensitivity (ELDRS), which can affect some types of bipolar/BiCMOS devices and integrated circuits

Document dates are current as of 09/2015.

Steps to perform a TID test



Flow diagram for ionizing radiation test procedure for MOS and digital bipolar devices



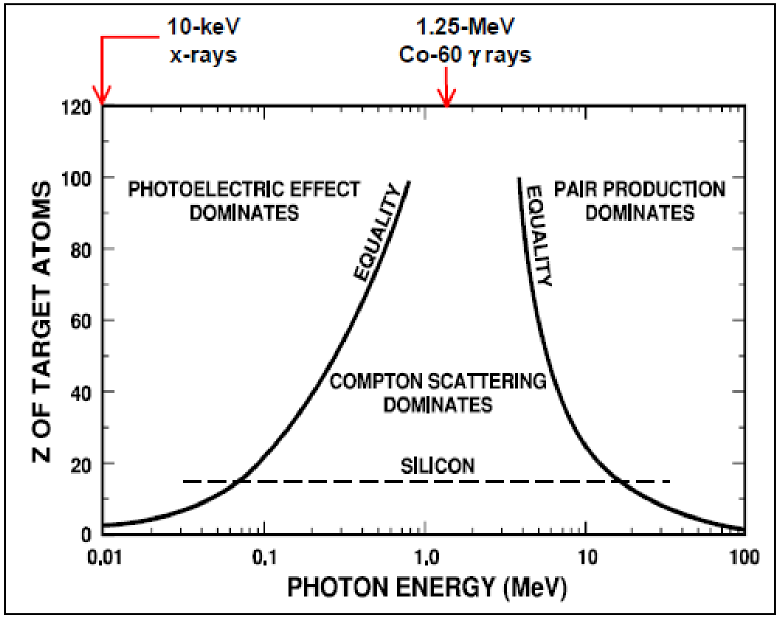
Flow diagram for ionizing radiation test procedure for bipolar (or BiCMOS) linear or mixed-signal devices.

MIL-STD-883 / Method 1019.9
June 2013

Document date is current as of 09/2015.

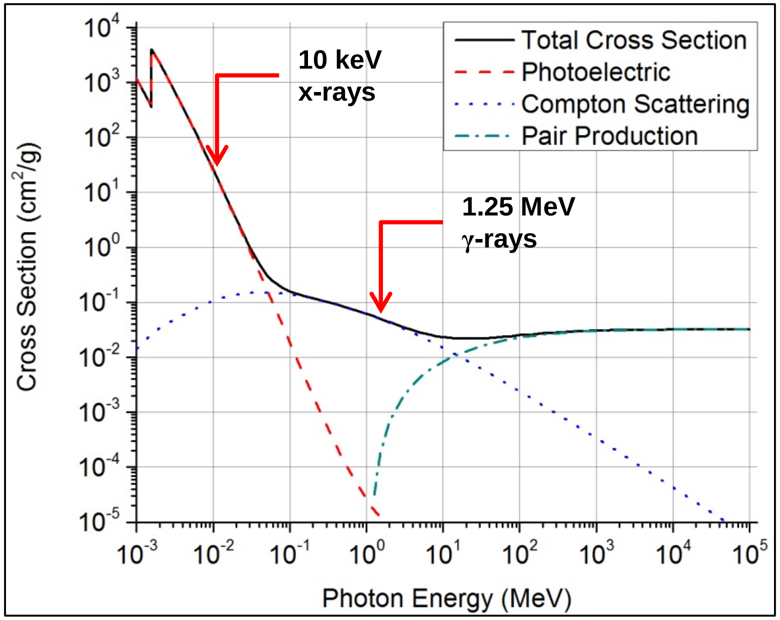
Issues with X-Rays *vs.* ^{60}Co γ-Rays

Photon Effects



R. D. Evans, *The Atomic Nucleus*, 1955.
After J. R. Schwank, *IEEE NSREC Short Course*, 2002.

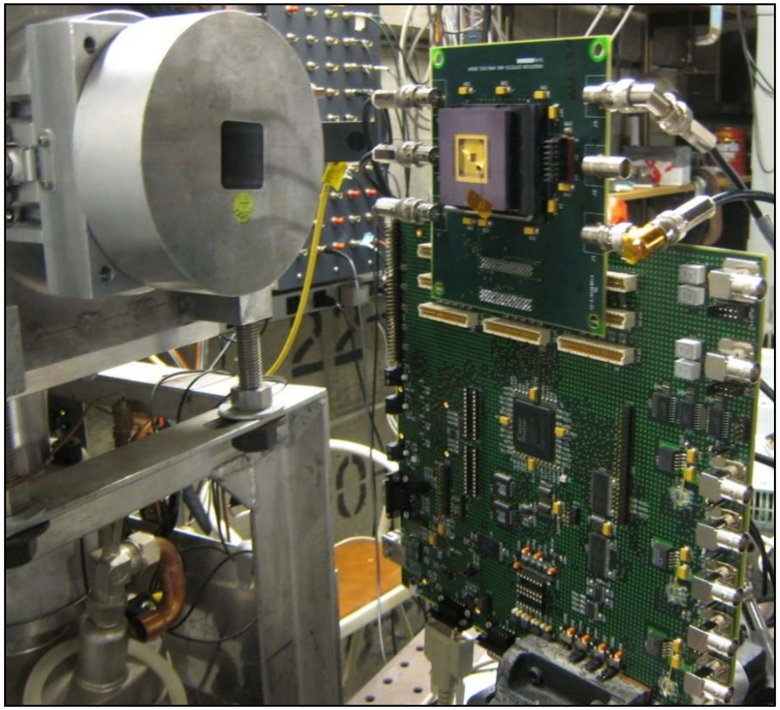
Photon Cross Sections in Aluminum



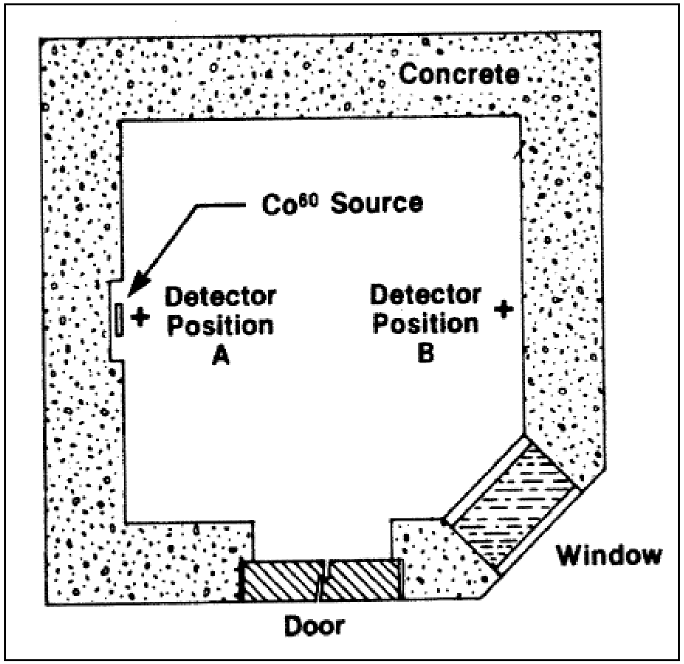
NIST XCOM Database; http://www.nist.gov/pml/data/xcom/index.cfm

- Practical terms: X-rays get absorbed more readily than gamma rays. For example, in aluminum:
  - 50% attenuation @ 1 mm for x-rays and 5 cm for γ-rays

In-situ evaluation



My cable run is 15 m!

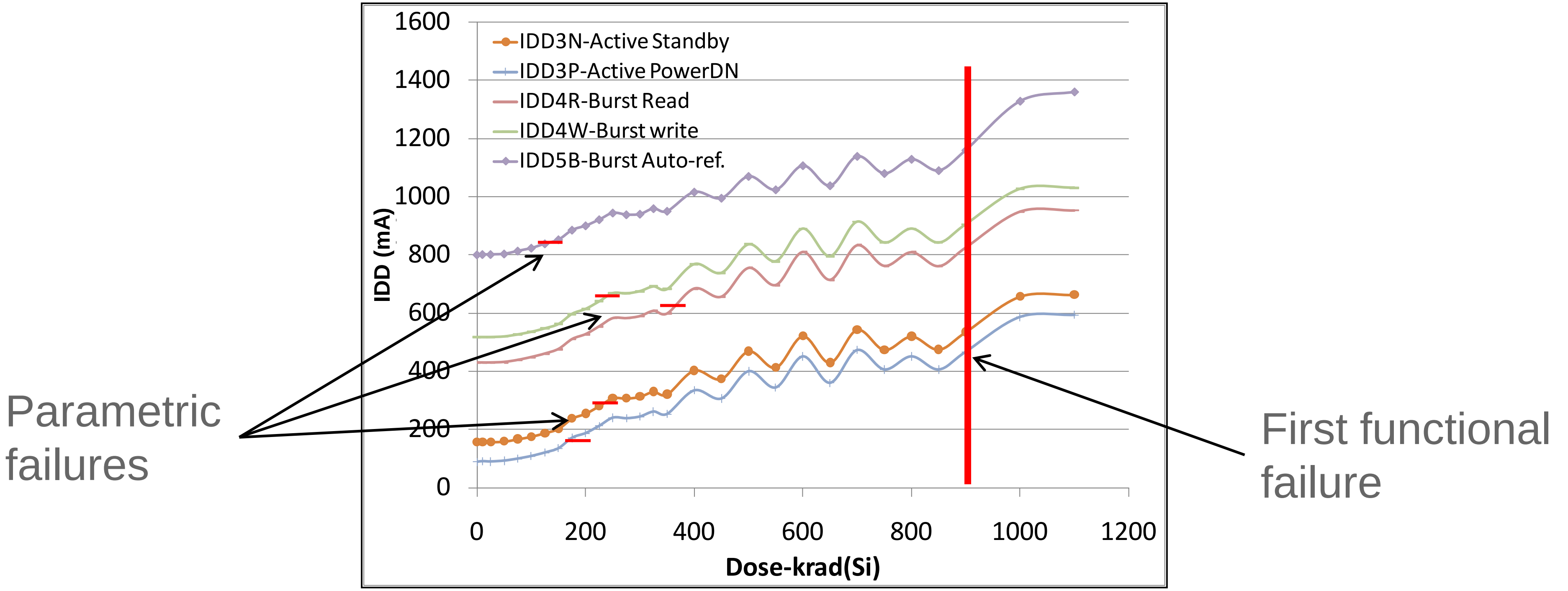


K. G. Kerris, *et al.*, *IEEE TNS*, 1985

- Can be difficult to route high-bandwidth and/or low-voltage signals long distances
- Can consider other irradiation sources

Black box components

Samsung DDR2 SDRAM

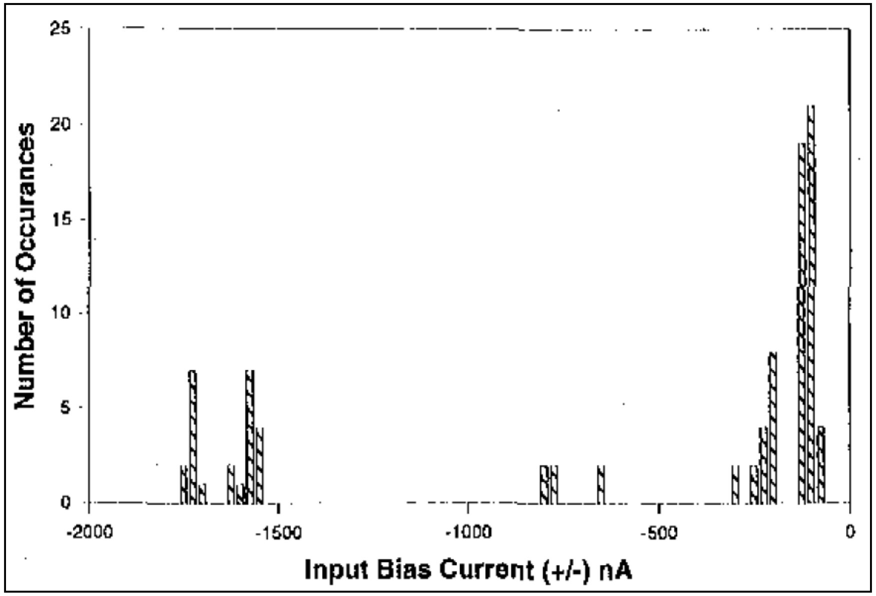


R. L. Ladbury *et al.*, *NEPP Electronics Technology Workshop*, 2011.

- Behavior indicates that failure dose not well correlated to observed degradation
- How do you track/predict potential failures?

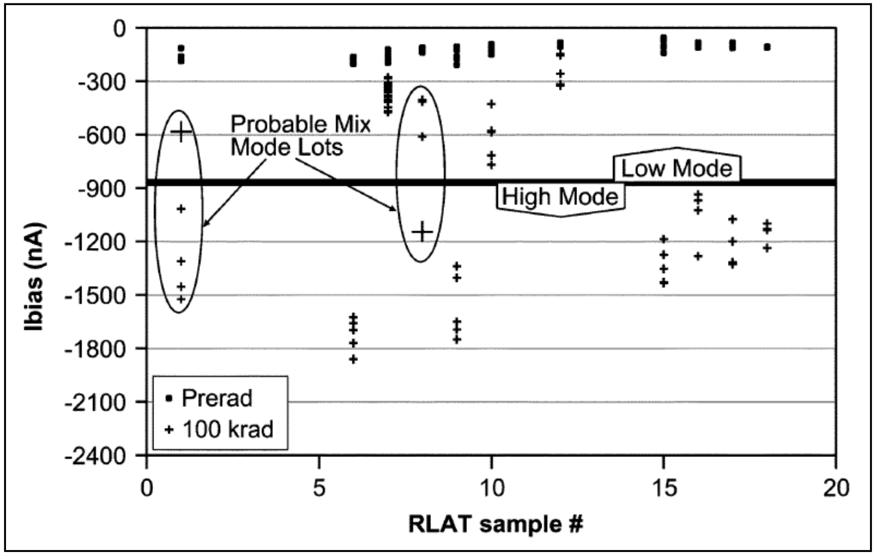
Component variability

LM111 Voltage Comparator at 50 krad(SiO_2)



J. Krieg, *et al.*, *IEEE TNS*, 1999.

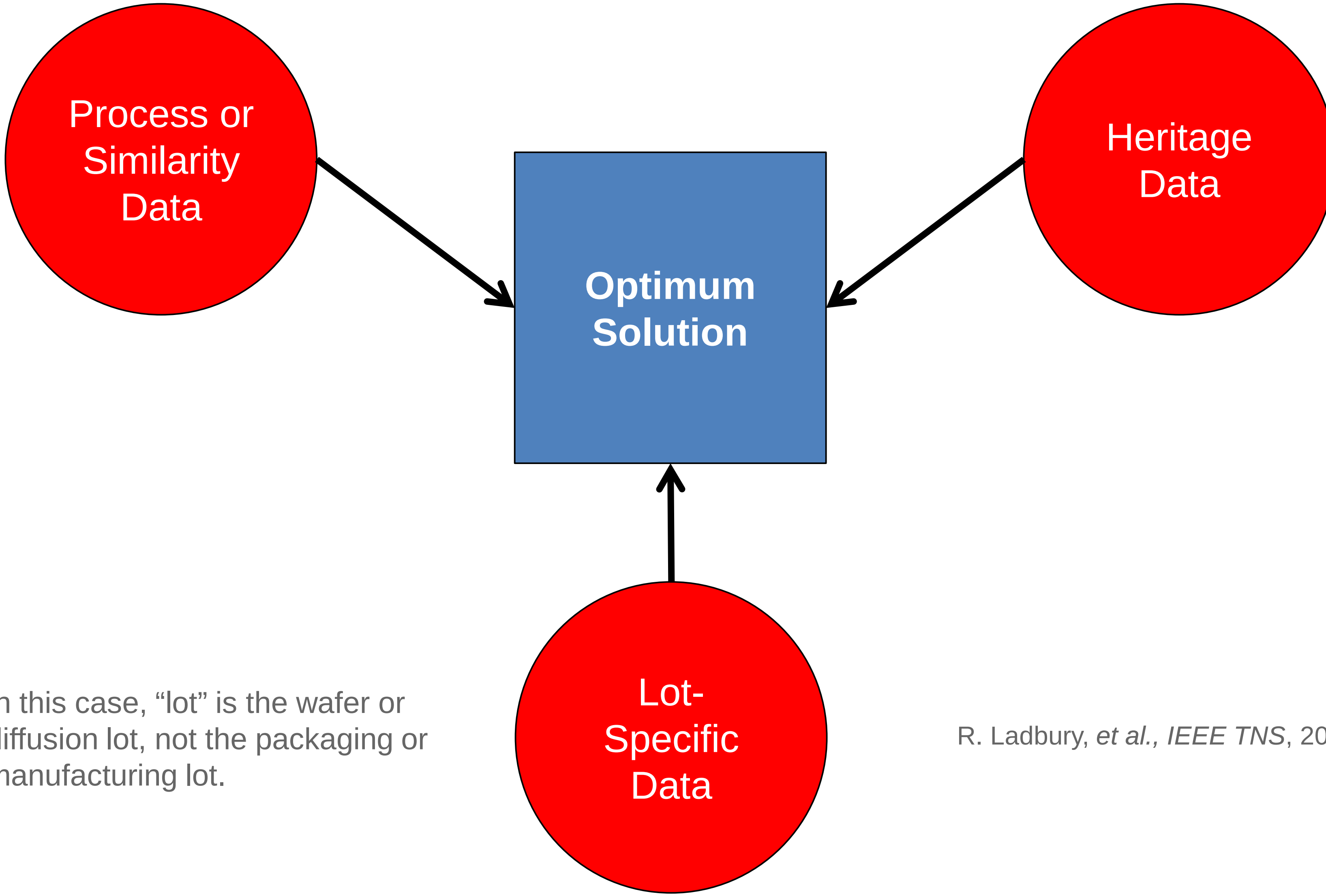
OP484 Quad Op Amp at 100 krad(SiO_2)



R. Ladbury, *et al.*, *IEEE TNS*, 2005.

- Sources of variability
  - o Process: defects, die position on wafer, implants,…
  - o Design: how much margin is left?

Bayesian analysis approach



In this case, “lot” is the wafer or diffusion lot, not the packaging or manufacturing lot.

R. Ladbury, *et al.*, *IEEE TNS*, 2011.

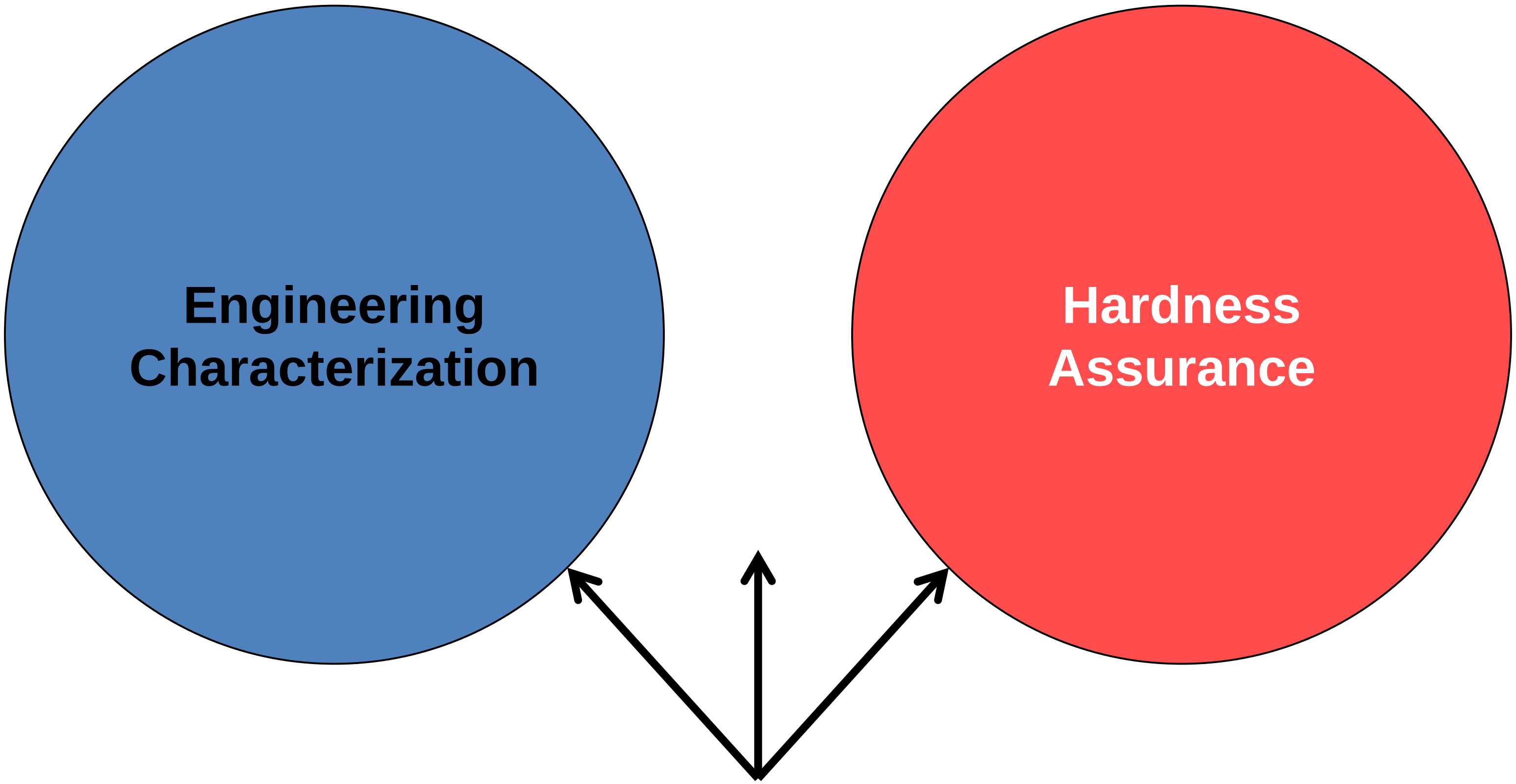
Possible TID testing solutions

Device complexity and dose rate sensitivity complicate TID evaluation and qualification

- Explore feasibility of non-photon radiation sources in some cases – can be good for comparison too
- Develop flexible interrogation methods for advanced, large-scale integration devices
- Increase lot test size to maximum practical extent
    - What distribution am I assuming? (normal, binomial, etc.)
- Leverage as much existing data as possible
- Track basic mechanisms research to maintain knowledge base on advanced material systems and latest simulation techniques

Evaluation of Single-Event Effects (SEE) in Advanced Electronics – *The death of averages*

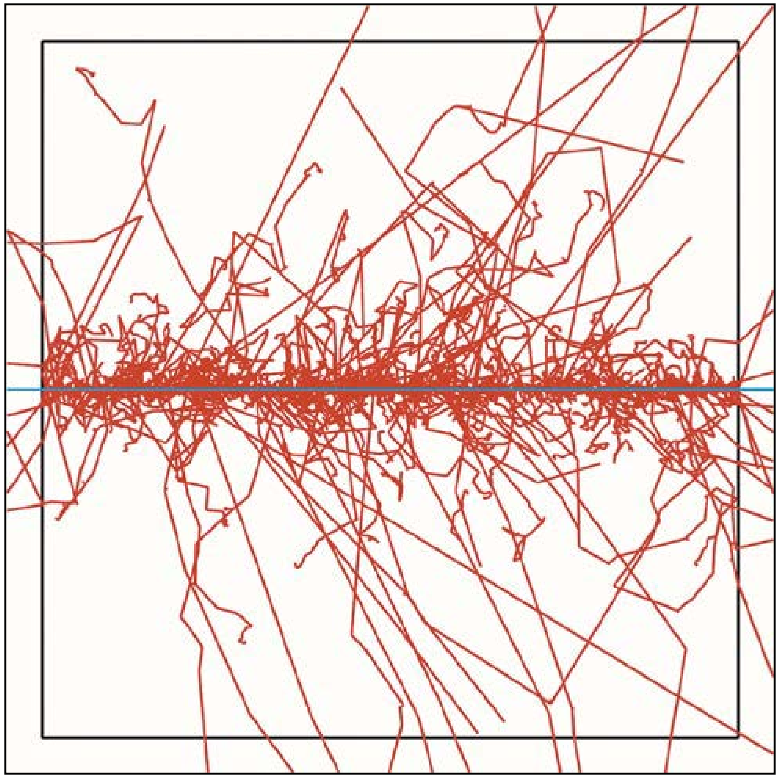
How do you approach testing advanced electronics?



Radiation testing protocols for advanced electronics

SEE complexity

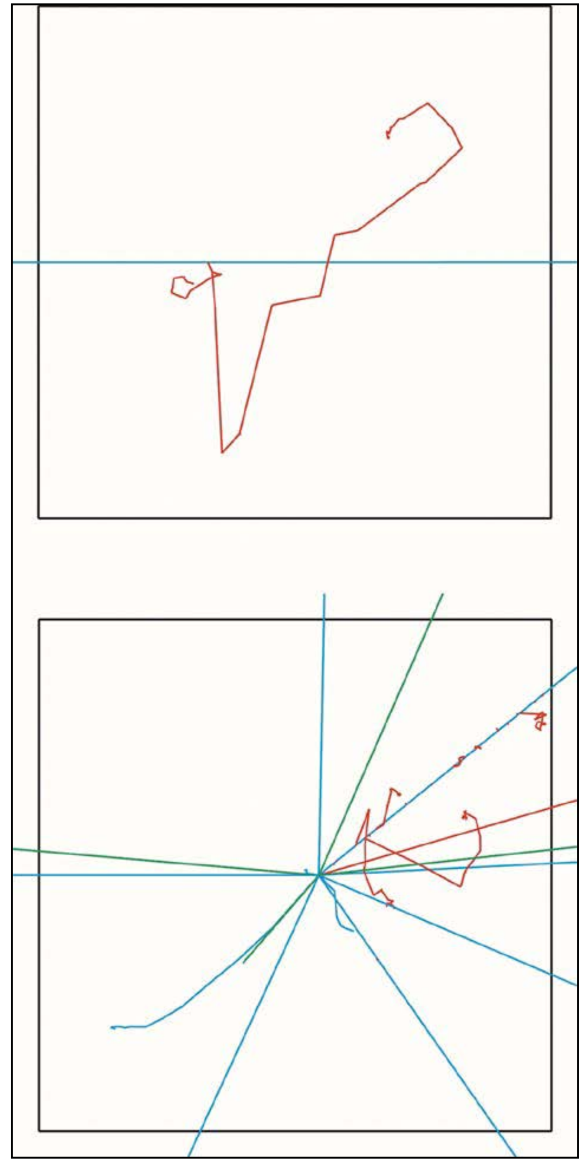
100 MeV protons in silicon



R. A. Weller, *et al., IEEE TNS*, 2003.

These pictures are what got me into radiation effects.

1 GeV protons in silicon



1 μm silicon cubes

Common SEE testing themes

- Difficulty of in-situ evaluation
    - "Test as you fly" implies application realism – maybe not appropriate
- Component complexity creates expensive "black boxes"
    - Many operational modes and on-board smarts
    - Test costs are spiraling upwards – "full" characterization not possible
- Advanced electronics have lead to:
    - Enhanced angular sensitivity due to process or design techniques
    - Sensitivity to low-energy protons and ??? (*e.g.*, muons and delta rays)
- Parameter space is HUGE
    - How do you evaluate an integral with 10s or 100s of dimensions?

SEE testing

- Why do testing?
  1. To determine the presence and characteristics of single events
     - » Destructive or non-destructive
     - » Voltage and temperature dependence
     - » Amplitude and width of SETs
  2. To calculate the SEE rate for a radiation environment
- SEE testing is usually done at accelerator facilities, which irradiate the whole device with ions. Some in-air and some in vacuum.
- Package must be opened, de-processed, thinned…
- Other testing methods that provide spatial and temporal information include:
  - o Focused, collimated ion beam
  - o Focused, pulsed laser beam

After S. Buchner, *SERESSA 2011 Course*, Toulouse, France.

Available SEE test methods

- Test guideline documents that define SEE testing of microelectronic devices and circuits *(last update):*
  - ASTM F1192 (10/2011)
  - ESCC Basic Specification No. 25100 (10/2014)
  - JEDS57 (12/1996; reaffirmed 09/2003 – being updated now)
  - JESD89 (10/2007; reaffirmed 01/2012)
  - MIL-STD-750, Method 1080 (04/2013)
- Do a reasonable job of defining procedures for heavy ion testing – *HOWEVER…*
  - Do not yet cover recently documented effects (*e.g.*, angular sensitivities, heavy ion indirect ionization) or proton SEE
  - Other guidelines and refereed publications exist

Document dates are current as of 09/2015.

Steps to perform a SEE test

- Understand device process technology and application conditions – SEE testing is most always application-specific
  - Could the device under test be susceptible to destructive effects?
  - Is there a target environment for qualification (requirements) or is the test an engineering characterization?
- Identify a suitable test facility and consider systematic variables
  - Ion selection, pulsed laser sources, energy range, flux range, dosimetry, beam profile and purity, and accelerator technology
- Develop a test matrix that covers necessary application space within allowable costs / schedule – the following can have large ranges:
  - Device function, data patterns, frequency, voltage/current, temperature, LET, energy, particle range, *etc*.
- Prepare devices for irradiation and travel to the test facility

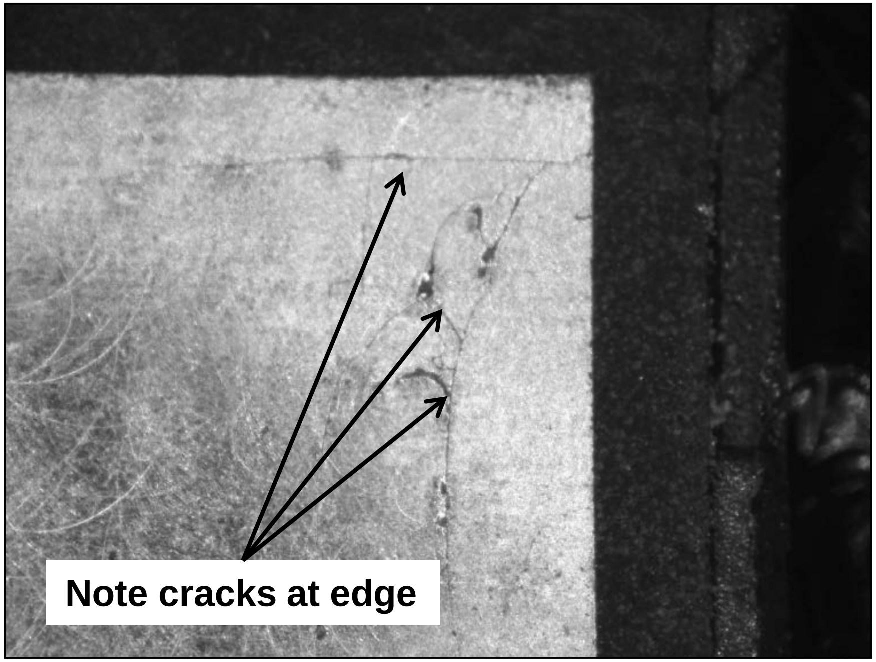
Steps to perform a SEE test

- The majority of time before, during, and after a SEE test is spent
  1. Deciding what you want to measure and how;
  2. Verifying you can do 1.; and,
  3. Figuring out what you actually got.
- Because SEE testing is real-time, many aspects are dynamic, so contingency planning is essential
- Always have a backup plan

Device preparation

- Thinning and polishing for backside irradiation is not trivial
- As with any commercial technology, destructive effects are always a concern – statistics?!?
- Repeatability concerns from lot-to-lot (packaging)

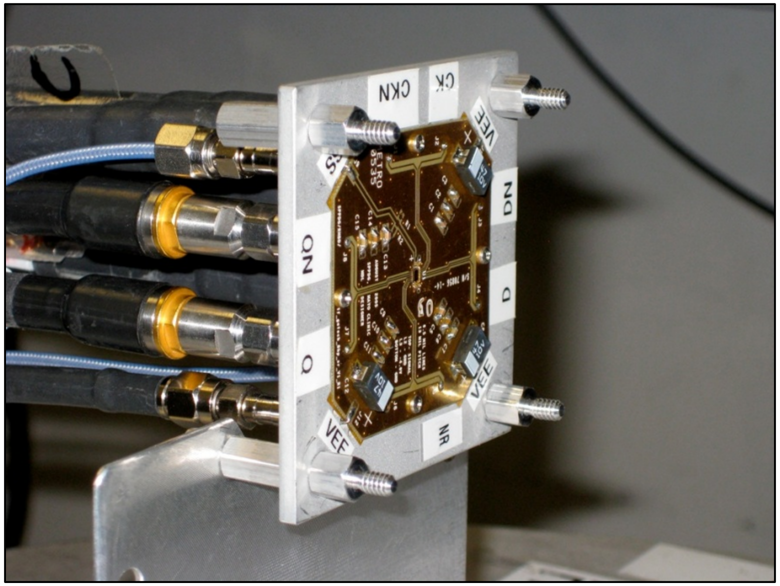
1 Gbit DDR2 SDRAM Die



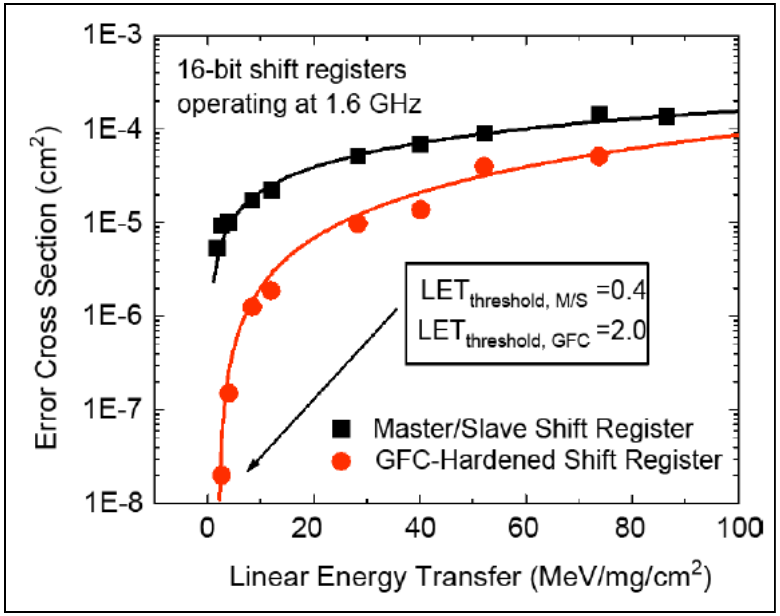
R. L. Ladbury, *et al.*, *IEEE Radiation Effects Data Workshop*, 2008.

In-situ evaluation

High-Speed Test Fixture



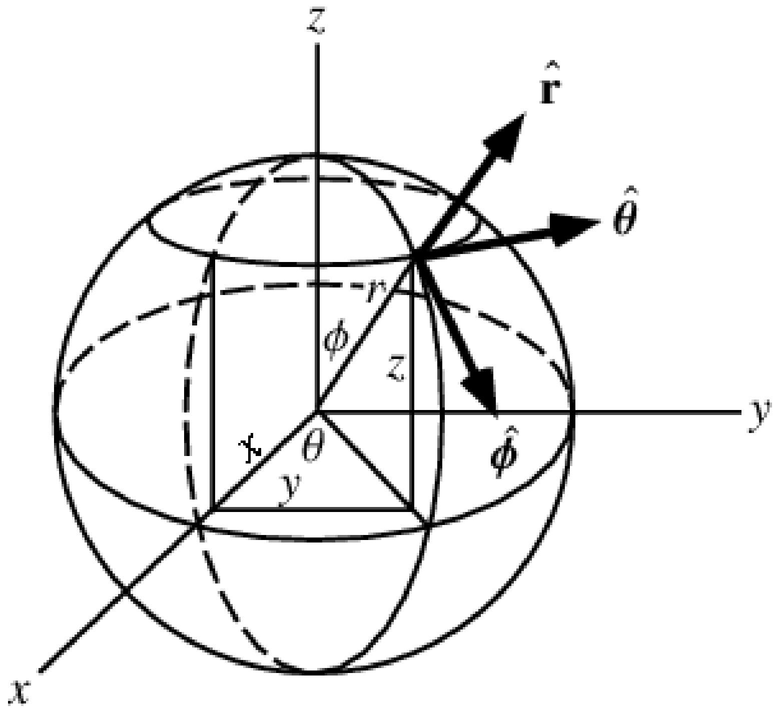
IBM 5AM SiGe HBTs



E. P. Wilcox, *et al.*, *IEEE TNS*, 2010.

- Special considerations for angle, bandwidth, and proton activation
- Similar approach with FPGA-based testers

Tilt *and* roll angle sensitivities

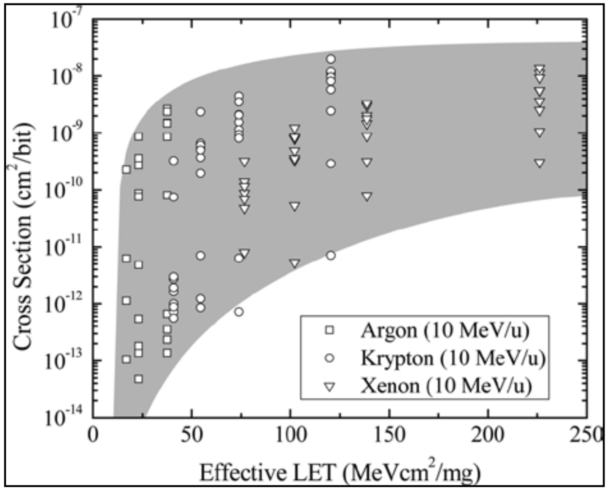


http://mathworld.wolfram.com/SphericalCoordinates.html

$$\Omega = 2\pi\left[1-\cos\left(\frac{a}{2}\right)\right]$$

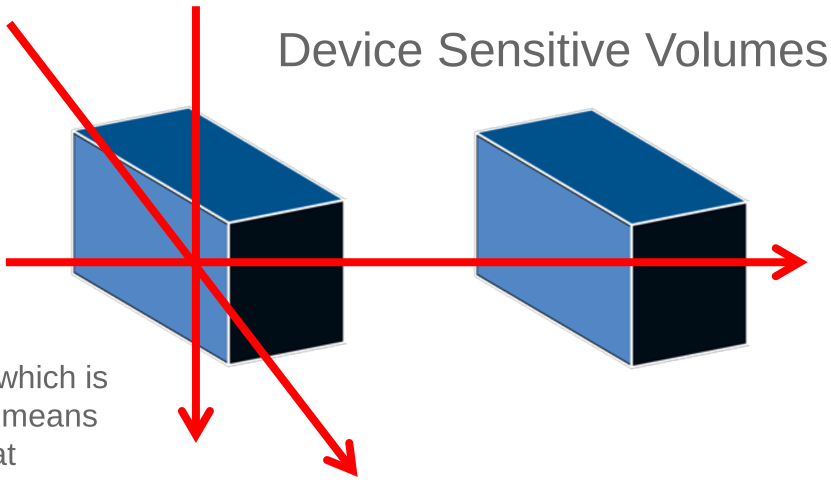
Solid angle for a cone – When the apex, a, is equal to 120°, Ω = π, which is half the solid angle subtended by the surface of a hemisphere. This means that half of the particles in an isotropic environment will be incident at angles below 60° and the other half at angles above 60°.

90 nm CMOS, RHBD Latch



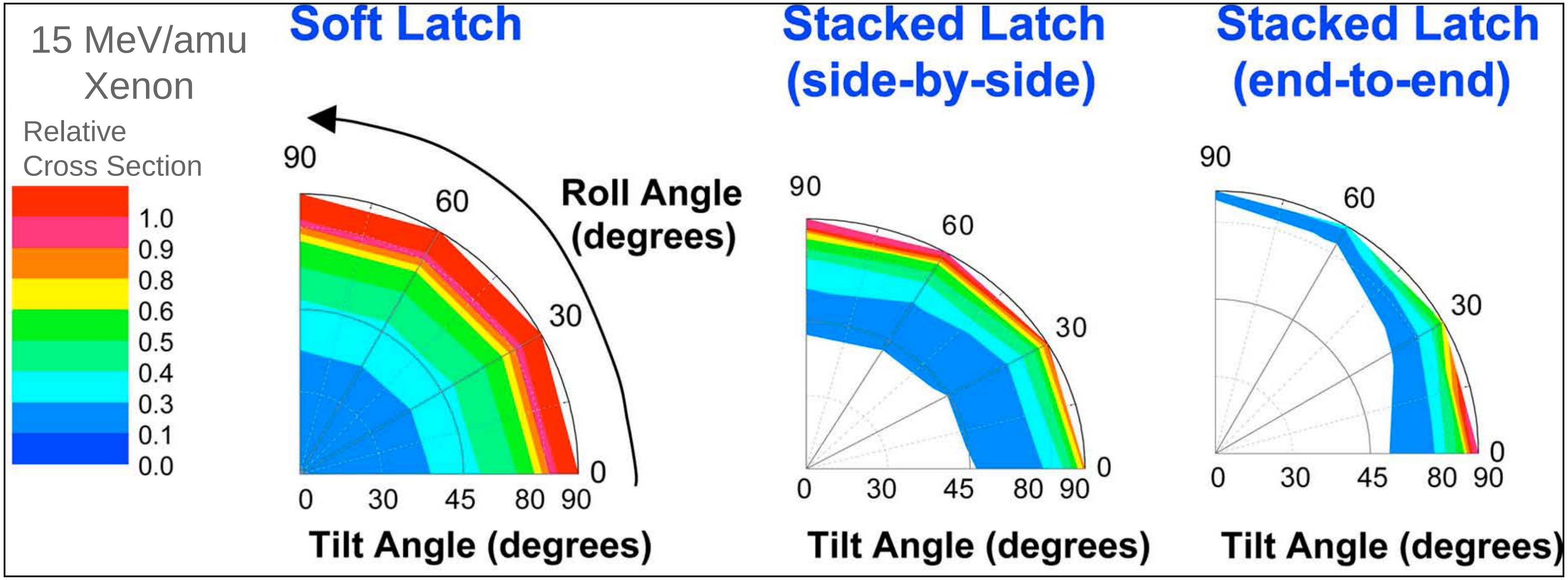
K. M. Warren, *et al.*, *IEEE TNS*, 2007.

Device Sensitive Volumes



Tilt *and* roll angle sensitivities

32 nm SOI CMOS latch cross sections – contours are based on data & simulation

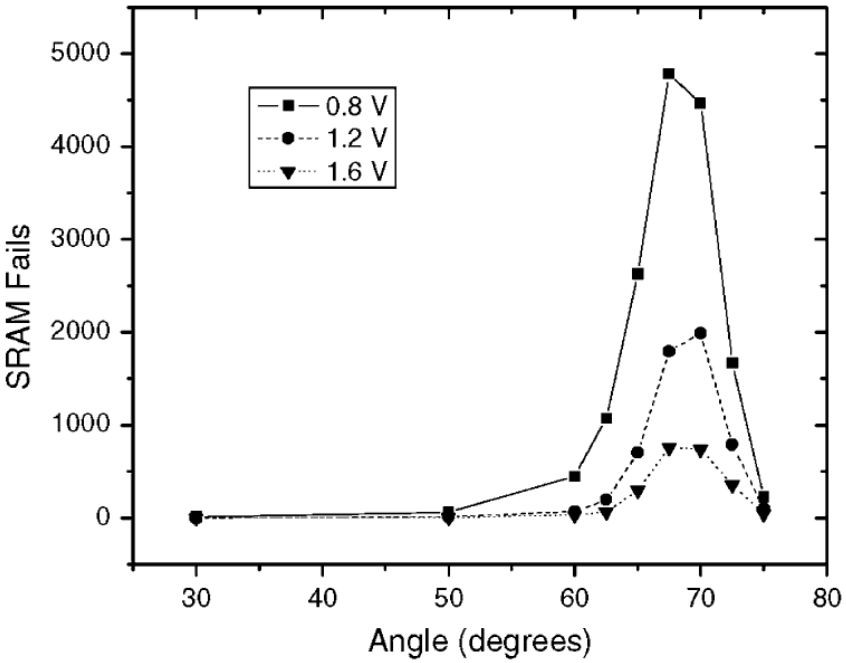


K. P. Rodbell *et al.*, *IEEE TNS*, 2011.

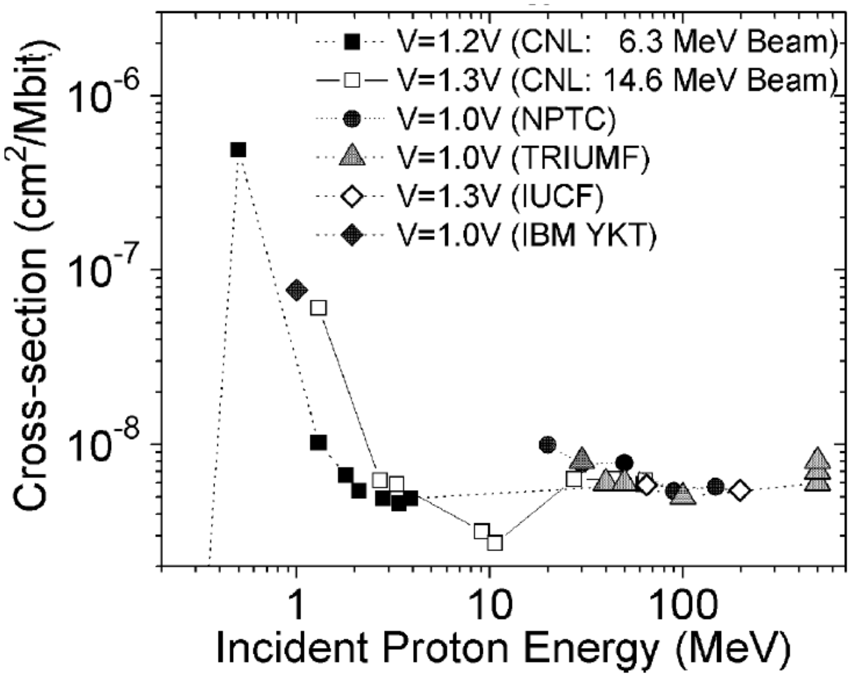
- Non-destructive SEE continue to be the most difficult aspect of advanced CMOS radiation effects
    - Varied angular sensitivity (test considerations)

Low-energy proton sensitivity

IBM 65 nm SOI SRAM – top-side irradiation



K. P. Rodbell, *et al.*, *IEEE TNS*, Dec. 2007.

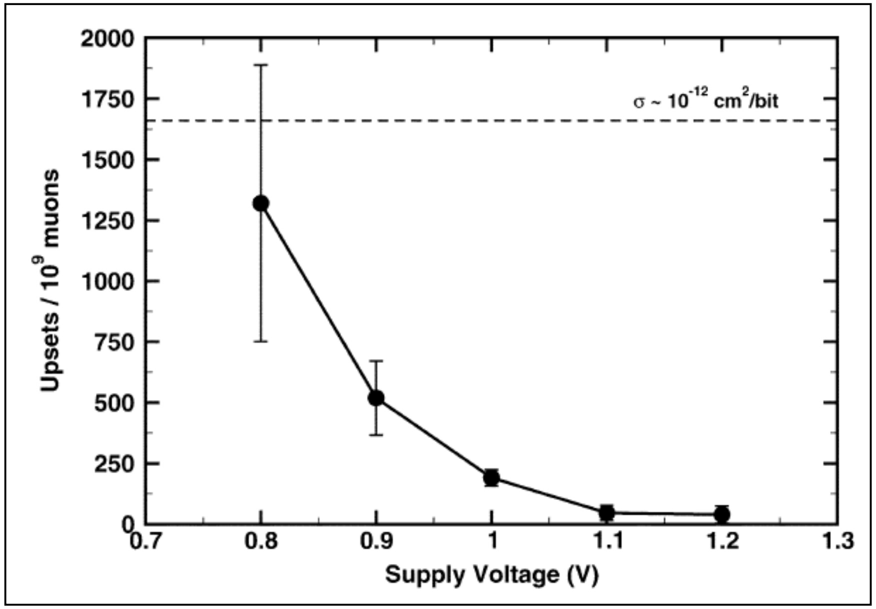


D. F. Heidel, *et al.*, *IEEE TNS*, Dec. 2008.

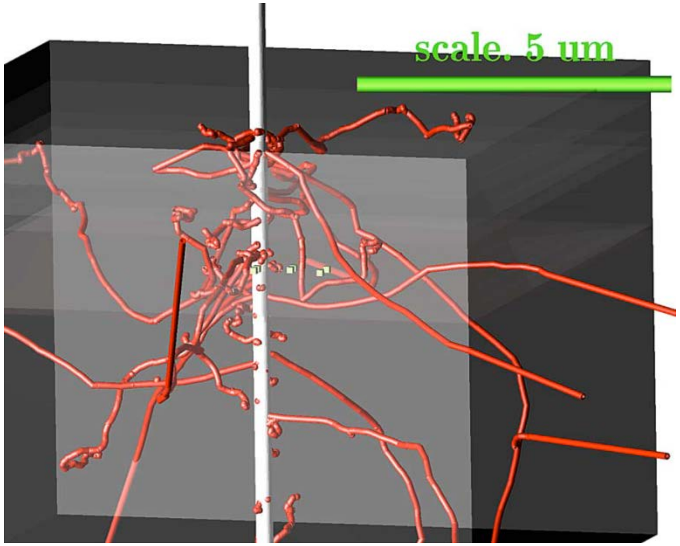
- First published low-energy proton soft errors in 2007
- Energy below Coulomb barrier – interactions are constrained to electromagnetic and nuclear elastic reactions
- Rapid cross section increase at grazing angles and energies below 2 MeV

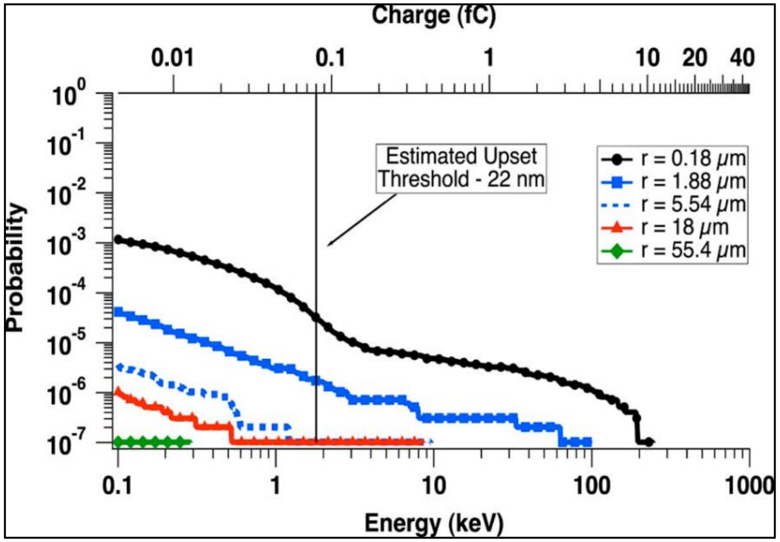
Beyond low-energy protons

400 keV muons on a 65 nm SRAM



B. D. Sierawski, *et al., IEEE TNS*, 2010.





28 GeV iron ions on SRAM structure and ensuing delta ray energy deposition.

M. King, *et al., IEEE TNS*, 2010.

Radiation test costs

- It’s expensive!
- Unavoidable non-recurring engineering because of custom setups and destructive nature of evaluation
  - Can be mitigated if there’s economy of scale
  - Test plan, design, fabrication, assembly, debug, test, analyze, reduce, repeat…
- Many external test facilities are ~$1000/hr
  - Travel and shipping costs to remote facilities
- Complicated, multi-month evaluations can top several $100K – even ≥$1M for the most complex devices and SoCs

Testing wisdom

No one believes an analysis – except the person who did it
Everyone believes a test – except the person who did it

- A test without requirements or an objective is not a test
- A test without a report did not happen

Course sections

1. Introduction
2. Natural space radiation environment
3. Space environment impacts
4. Component selection and radiation effects mitigation
5. Radiation testing
6. **Conclusion**